1980

Evaluation of a subsonic cascade wind tunnel for compressor blade testing.

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http://hdl.handle.net/10945/17580

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

EVALUATION OF A SUBSONIC CASCADE WIND TUNNEL

FOR COMPRESSOR BLADE TESTING

By

David A. DuVal

September 1980

Thesis Advisor: R. P. Shreeve

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Evaluation of a Subsonic Cascade Wind Tunnel For Compressor Blade Testing		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis September 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David A. DuVal		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, Ca 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, Ca 93940		12. REPORT DATE September 1980
		13. NUMBER OF PAGES 86
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, Ca 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cascade wind tunnel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

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Evaluation of a Subsonic Cascade Wind Tunnel For Compressor Blade Testing

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1980

ABSTRACT

Development of the subsonic cascade wind tunnel facility required determination of the two-dimensionality and periodicity of the airflow in the test section with test cascade installed. Data acquisition procedures were developed, and data were recorded for two facility configurations. The flow was shown to be unsatisfactory at a diffusion factor of approximately 0.58 and aspect ratio 1.25, and to be acceptably two-dimensional and periodic at a diffusion factor of approximately 0.39 and aspect ratio 1.95.

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LIST OF SYMBOLS

AVDR	Axial velocity-density ratio
D	Diffusion factor
Q	Dynamic pressure
R	Gas constant for air
T	Temperature (R)
V	Velocity (ft/sec)
X	Velocity, non-dimensionalized by the "limiting" velocity $V_T = \sqrt{2c_p T_T}$.
c	Blade chord (inches)
h	Streamtube depth (spanwise direction)
i	Incidence angle (degrees)
k	Mass flux rate, non-dimensionalized by a reference mass flux rate
m	Mass flux rate per unit area
p	Pressure (in. H_2O)
s	Blade-to-blade spacing (inches)
t	Time parameter
β	Air inlet angle, measured in blade-to-blade plane (degrees)
γ	Stagger angle (degrees)
δ	Deviation angle (degrees)
η	Blade-to-blade distance (inches)
ρ	Density (slugs/ft^3)
σ	Solidity (c/s)
ϕ	Pitch angle (of air flow), measured in spanwise plane

φ	Camber angle (degrees)

Subscripts:

a	Ambient, atmospheric
i	Refers to traversing plane; $i = 1$ for inlet, $i = 2$ for outlet
j	Indicates a discrete point in time
kiel	Refers to measurements taken with (stationary) Kiel probe
plen	Plenum (supply)
ref	Reference
s	Static
T, t	Total

Superscript:

*	Indicates quantity calculated using plenum pressure as $p_{t_{ref}}$, rather than Kiel probe pressure.

I. INTRODUCTION

The work reported herein was to evaluate a subsonic cascade wind tunnel facility, and, in particular, its suitability for measurements of air flow through two-dimensional cascades of compressor blades. Detailed flow field data are needed from carefully controlled tests in order that newly emerging flow prediction computer methods can be tested and refined. Blade element performance data are also needed for new blading designs.

Theoretical flow through cascades of blades and application of theoretical and experimental data to the design of axial flow compressors are treated in Reference 1. Chapter 6 of Ref. 1 collects and summarizes the extensive early cascade studies carried out at NACA. The importance of obtaining the proper two-dimensional and periodic flow is emphasized. In view of the unique design of the present facility (Figures 1 and 2) however, it was not certain that the experiences of other investigators would necessarily be repeated.

Before subsonic cascade wind tunnel data can be accepted as valid, the flow conditions in the tunnel must meet three criteria. Reference 2 discusses these criteria in detail. First, the inlet flow must be acceptably uniform. Any disturbances in the airflow should be caused by the cascade of test blades, and should not pre-exist in the wind tunnel. Static, dynamic, and total pressures, and the flow direction, should be uniform over the cross-section as the flow enters the test section.

Secondly, the flow passing through the test blading must be two-dimensional; that is, measured flow characteristics must be reasonably independent of spanwise position. The standards by which two-dimensionality

are measured are discussed in Section II.

The third criterion is periodicity of the near-field inlet flow and of the outlet flow. In the near-field (within about one chord length of the blades), as the airflow approaches the leading edges of the blades, an upstream perturbation occurs as the streamlines adjust to negotiate the blade passages. Since the test cascade is intended to simulate an infinite cascade of blades, the flow characteristics should be the same at corresponding locations in all inter-blade passages. This condition should also hold true at the outlet of the blading.

Earlier work by Moebius (Ref. 3) with the present facility involved modifications to the plenum chamber which established satisfactorily uniform flow at the exit of the bellmouth contraction into the test section. The purpose of the present study was to determine whether or not sufficiently two-dimensional and periodic flow could be produced through typical compressor cascade configurations within the available range of blade aspect ratios, but without the removal of tunnel wall boundary layers by suction. The study was preliminary to, and motivated by, a NASA requirement to obtain test data on specific cascade geometries.

The notation used to describe the test cascade is given in Figure 3. Tests were made with two configurations. First, seven NACA 65-series blades were installed at an air inlet angle, $\beta_1 = 60$ degrees and a stagger angle, $\gamma = 46.1$ degrees. Surveys of the flow, using the instrumentation system reported in Ref. 3, showed that the flow at the cascade outlet was grossly distorted and certainly far from being two-dimensional. Preliminary results obtained with this configuration are reported in Appendix A. A cascade of fifteen C-series blades was then installed at an air inlet angle, $\beta_1 = 39.8$ degrees and stagger angle, $\gamma \doteq 16.21$ degrees. The air inlet angle

and diffusion factor (Ref. 1, Chapter 6) were chosen to approach, as nearly as possible, those required in the first cascade to be tested for NASA. The results of the experimental program, and the instrumentation and data acquisition procedures developed for future cascade testing, are reported in the following sections.

II. EXPERIMENTAL CONSIDERATIONS

Uniformity of the inlet flow field, two-dimensionality at mid-span, and periodicity from blade to blade are necessary (but not sufficient) conditions for obtaining valid cascade data. In what follows, the necessary conditions will first be discussed, then additional experimental requirements will be mentioned.

The requirement for uniformity of the inlet flow is common to all wind tunnel testing. In the present facility, verification was needed that the inlet guide vanes to the test section produced an acceptably uniform flow ahead of the test blading.

The second condition is that a substantial portion of the span (at all stations in the blade-to-blade direction) must exhibit uniform flow characteristics. This will clearly depend on several factors. If the flow were truly two-dimensional, the flow characteristics would be completely independent of the spanwise location in the cascade. Boundary layers develop, however, along the side and end walls between the entrance to the test section and test cascade. Within the boundary layers, the total and dynamic pressures are lower than they are in the main stream. The growth of the boundary layers causes an effective contraction of the main stream cross-sectional area, with the result that the velocity and dynamic

pressure in the main stream are slightly higher than they would be in truly planar, two-dimensional flow. In other installations (Ref. 2, for example), this problem was reduced by removing the boundary layers using suction through porous walls. One of the objectives in the design of the present wind tunnel was to reduce the need for suction by ensuring uniform boundary layers on the side walls in the blade-to-blade direction, and by operation at high Reynolds' numbers. A further difficulty caused by the development of the wall boundary layers is their interference with the boundary layers that form on the surfaces of the blades in the cascade. It is especially difficult to establish a substantial spanwise area of uniform flow in the region near the suction side of each blade (Ref. 2).

In planar, two-dimensional flow through a channel (i.e., the flow has the same cross-sectional depth at inlet and outlet), continuity requires that the product of fluid density and axial velocity remain constant. In the cascade wind tunnel, the buildup of boundary layers along the tunnel walls, and their interference with boundary layers developed on the blades, causes the effective spanwise depth of streamtubes in the main flow near mid-span to contract. This results in the product of fluid density and axial velocity being slightly higher in the main stream at the outlet of the cascade than at the inlet. The ratio of the product at the outlet to that at the inlet is generally referred to as the axial velocity-density ratio (AVDR). An AVDR of unity would indicate a perfectly two-dimensional flow, while values other than unity indicate departures from this condition.

The third necessary condition is that the flow be periodic from blade to blade. When the cascade has few blades (say, seven or fewer), the two (incomplete) passages, between each end wall and the first adjacent blade, become critical. Flexible and porous walls have been used to, in effect,

control the bounding streamlines in these regions (Ref. 2). Clearly, as the number of blades in the cascade is increased, subject to a satisfactorily uniform inlet flow, the end passages become less critical, and periodicity will be more easily achieved over the center blades. Periodicity can be verified by flow field measurements or, more sensitively, by comparing surface pressure distributions measured on different blades.

When upstream uniformity, spanwise two-dimensionality, and blade-to-blade periodicity are acceptable, probe survey data from upstream and downstream of the blades can be taken and integrated to obtain the two-dimensional blade-element performance. However, one further condition must be met: The survey data must satisfy the momentum conservation equation for the particular value of the AVDR obtained by satisfying continuity.

As the air is turned in passing through the cascade, the change in its momentum can be calculated from the angles and velocities at the inlet and outlet. The change in momentum (measured at the spanwise centerline) is related to the force on the blades and the change in static pressure across the cascade. Integration of the measured pressure distribution along the centerline of the blade (in the chordwise direction) yields the pressure force exerted by the blade section on the air. Comparison of the measured pressure force with that calculated from the change in momentum of the air is the final verification that the proper experimental flow conditions have been established. To date, a comparison of the pressure forces on the blades with those calculated from the changes in momentum has not been made, since blades instrumented with pressure taps have not been available.

III. FACILITY DESCRIPTION

A. CASCADE WIND TUNNEL

The subsonic cascade wind tunnel facility was described by Moebius [3] and, in detail, by Rose and Guttormson [4]. Figure 1 shows the layout of the facility and its unique test section design. The design ensures that the airflow paths from the guide vanes to all blades of the cascade are of equal length. This was intended to eliminate the problems in other designs caused by having wall boundary layers of different thicknesses (and histories) entering the cascade at different points. Figure 2 shows a photograph of the cascade wind tunnel test section.

B. INSTRUMENTATION

The position of the instrumentation is shown in Figure 4.

1. Wall Pressure Taps

Static pressure taps were located on the south side wall, 15.25 inches axially ahead of the mid-chord and 7.25 inches axially behind the mid-chord of the cascade of 5.12 inch (chord) blades. Twenty taps were evenly spaced at two inch intervals along the wall in the blade-to-blade direction at each axial location. The taps were connected to a water manometer board so that the uniformity of the static pressure distribution in this direction could be monitored visually. One upstream tap and one downstream tap (near the centerline) were also connected to the Scanivalve, through which all pressures were recorded.

2. Upstream Reference Probe

A fixed Kiel probe was placed on the spanwise centerline in the test section downstream of the turning vanes, but well upstream of the cascade.

The probe provided a reference total pressure during the tests. The probe was also connected to the Scanivalve.

3. Upstream Survey Probe

A United Sensor Corporation DA 125 probe, Serial no. A847-1 (described in Ref. 5 and Appendix B) was mounted in a traversing mechanism approximately 11.25 inches axially upstream of the cascade, such that it could be positioned anywhere within a section 10 inches wide by 24 inches long of the inlet flow cross-section. The probe pneumatic pressures were connected to the Scanivalve, and position and yaw angle of the probe were recorded using position potentiometers.

4. Downstream Survey Probe

A United Sensor Corporation DC-125-24-F-22-CD probe, Serial no. A981-2 (described in Ref. 5 and Appendix B) was positioned approximately 11.75 inches axially downstream of the cascade. Its mounting and data acquisition were identical to those of the upstream survey probe.

5. Survey Rake

A rake of static and total pressure probes (described in Appendix C) could be substituted for either survey probe. The rake spanned the test section and was used to survey in the blade-to-blade direction. Measurements were made with the rake mounted in the downstream traversing mechanism. The rake pressures were connected to the Scanivalve, and the rake yaw and blade-to-blade position were also recorded.

6. Reference Measurements

Plenum chamber (supply) pressure and temperature, and atmospheric pressure, were recorded with each data scan. The total temperature throughout the test section was assumed to be the same as the plenum chamber temperature.

C. DATA ACQUISITION AND REDUCTION

The data acquisition system is shown in Fig. 5. Data was logged, reduced, and plotted using the Hewlett-Packard HP-3052A Data Acquisition System (see also Ref. 6). The system used an HP-9845A calculator as a controller, with components interconnected on an HP-98034A HP-IB Interface Bus, including an HG-78K Scanivalve Controller (Ref. 7).

The programs developed during the present study for acquisition, reduction, and plotting of data from the cascade wind tunnel are listed and described separately in Reference 8.

IV. TEST PROGRAM AND PROCEDURES

A. PROGRAM DESCRIPTION

Table I gives data for the two cascade geometries which were tested. In the first configuration, the cascade consisted of seven 10 % thick NACA 65-series airfoils of eight-inch chord, spaced eight inches apart. The inlet end-wall angle was set at 60 degrees. The stagger angle (for minimum loss incidence) was set at 46.1 degrees, and the calculated outlet angle was 40 degrees. The outlet end wall was therefore set to 40 degrees. The calculated diffusion factor was $D = 0.577$. In this configuration, one side wall ("side walls" are those perpendicular to the blade span) was steel, while the other was one-inch-thick plexiglass.

In the second configuration, measurements were first made with no blades in the test section, and with the test section inlet air angle, $\beta_1 = 39.8$ degrees. The purpose of this test was to ensure first that the flow from the guide vanes into the test section was satisfactorily uniform before inserting the test blades. A cascade of 15 C-series airfoils was then

inserted. The blades had a chord of 5.12 inches and were spaced four inches apart, for a solidity of approximately 1.28. Two-dimensionality was expected to be improved by the higher aspect ratio, but the Reynolds' number was necessarily reduced. The inlet end wall angle was set at 39.8 degrees, for an incidence angle calculated to be 10 degrees above the calculated minimum loss incidence angle. The outlet end walls were set at 12.8 degrees. These values were calculated to achieve a diffusion factor of 0.394. In the second configuration, the one-inch plexiglass wall was replaced with the facility's original steel wall (Ref. 4), since the plexiglass wall was observed to have bowed. Care was taken with the end-blade-to-end-wall passages as described in Reference 9.

B. PROCEDURE

The procedure used in testing the second configuration was as follows. With the tunnel running, and before data were taken, the outlet end walls and the inlet guide vanes were iteratively adjusted to produce a very nearly uniform distribution of static pressure across the inlet and outlet to the cascade, as monitored by a multitube water manometer bank. The adjustment procedure is described in Reference 9.

The rake probe was used first to survey the outlet plane to determine quickly whether any spanwise area of uniform flow existed. Integration of the calculated mass flux (using rake impact pressures and side wall statics) on the spanwise centerline of the tunnel was compared with the mass flow rate estimated at the lower plane using the Kiel probe pressure and the inlet side wall static pressure measurements. This gave a rough approximation of the AVDR. Periodicity of the flow was checked by comparing values of total pressure at corresponding locations in different blade passages.

Detailed surveys of both the inlet and outlet planes in the blade-to-blade direction were then undertaken with the survey probes (described in Appendix B). Integration of inlet and outlet mass flux distributions derived from the survey measurements was performed to determine the AVDR using the method described in Appendix D. The data also provided a confirmation of the periodicity of the flow.

All tests were carried out with a plenum pressure to atmospheric pressure difference of 16 to 20 inches of water.

V. RESULTS AND DISCUSSION

A. FIRST CONFIGURATION

The results presented in Appendix A for the first configuration showed that the flow at the cascade outlet was distorted and not symmetrical about the mid-span plane. The degree of spanwise non-uniformity was quite unsatisfactory. The non-uniformity may have been due to stalling of part of the cascade, aggravated by leakage between the blade ends and the plexiglass wall. It is also suspected that the technique of using both survey probes at once was improper, since the downstream survey probe was then in the wake of the upstream survey probe. The accuracy of the downstream probe data is therefore questionable.

B. SECOND CONFIGURATION

Tests were first conducted with the cascade blades removed to determine the effect of the guide vanes at the test section inlet. Results obtained with the rake probe are reported in Ref. 9. It was found that the wakes from the vanes were not mixed out at the lower measuring plane but gave a well defined periodic variation in the impact pressure. This condition was

undesirable, but it could be tolerated while looking only at two-dimensionality and periodicity. Since inlet flow conditions were not uniform, mass averages would be used to calculate properties at the inlet plane from probe measurements.

Data from the rake probe surveys downstream of the blades in the second cascade configuration are listed in Table II and shown plotted in Figures 6 - 13. A photograph of the water manometer board showing the side-wall static pressures upstream and downstream of the cascade is shown in Figure 14. The static pressure was seen to be uniform at both stations to within 0.1 inches of water following the adjustment procedure described in Ref. 9.

Figures 6, 7, and 8 show plots of spanwise total pressure distributions at discrete blade-to-blade locations. Figure 9 shows the distribution over one blade passage as a three dimensional plot. The data show a satisfactorily uniform distribution of total pressure over almost 50 percent of the span at all stations. From these data, the AVDR was estimated to be about 1.03.

Figures 10, 11, 12, and 13 show the spanwise total pressure distributions at corresponding positions in the four centermost blade passages. The figures show that the periodicity of the outlet flow, particularly near center span, was excellent.

The results of individual probe surveys at the upstream and downstream measuring planes at midspan are given in Figures 15 - 18. First, the flow angle variations are shown in Figures 15 and 16. There was measured to be less than $\pm$ 0.5 degrees variation upstream of the cascade, and less than $\pm$ 0.75 degrees variation downstream. The results in Figure 17 are shown for a blade-to-blade survey across four blade spaces, plotted over a single blade space. There was seen to be an apparent lack of periodicity in the

results in contrast to the rake results, and an explanation was needed. The data in Fig. 17 are shown for impact pressure in relation to the upstream (fixed) Kiel probe pressure, normalized to the supply dynamic pressure calculated from the Kiel probe and wall static pressure measurements. This method of normalizing the distribution would be expected to yield results which would not depend significantly on fluctuations in the supply conditions. However, that conclusion in turn requires that the Kiel probe measurements follow the supply fluctuations linearly. If the inlet flow were truly uniform, this condition would be satisfied automatically. The guide vanes at the test section inlet, however, generated wakes which were not at all well mixed at the Kiel probe (or, as can be seen in Fig. 18, at the inlet traversing plane). The consequence was that the Kiel probe, being in the wake of a guide vane, measured a reference total pressure which did not vary linearly with the mass-averaged total pressure at the inlet measuring plane. An examination of the probe and reference quantities recorded for the data in Fig. 17 showed that the survey probe pressure and the wind tunnel supply (plenum) pressure qualitatively followed the same trends, whereas the Kiel probe pressure did not. The examination also showed that the level of the supply pressure was slightly higher during the probe traverse (shown in Fig. 17) from 0 to +8 than it was during the traverse from -8 to 0. The data were therefore re-reduced by normalizing with respect to plenum supply pressure and a dynamic pressure based on plenum supply pressure and lower wall static pressure ($Qref^*$). The results are given in Table III and are shown plotted in Figures 19 and 20. It can be seen that periodicity of both the inlet and exit flow was again confirmed, and that apparent fluctuations in the data were reduced. It was concluded that a single fixed Kiel probe measurement at the lower plane was an

inadequate reference for cascade performance measurements in view of the presence of the inlet guide vane wakes.

It should also be noted that the presence of the small (1/8") Kiel probe positioned upstream of the lower measuring plane (Fig. 4) was detectable in the measurements made at the downstream plane when the test blading was removed. The irregular distribution of the rake pressures shown in Fig. 21 was found to be due to the presence of the Kiel probe when positioned near the center of the test section in the inlet flow. The near symmetrical distributions shown in Fig. 13 were obtained when the Kiel probe was moved well off center so that its wake would not be encountered in the surveys conducted at the upper measurement plane.

Variations in the blower speed (and therefore in inlet dynamic pressure) during the probe survey also presented difficulties in calculating the AVDR. The mass flux calculated at each point in the probe survey must be normalized to a reference mass flux in order to reduce the effect of time-varying inlet conditions. The procedure adopted, which is given in Appendix D, was to calculate a reference mass flux for each point in the survey using plenum pressure as the reference total pressure and lower wall static pressure as the reference static pressure. By integrating the mass flux ratio at both upstream and downstream planes over an integral number of blade passages, and taking the ratio of the two integrals, the AVDR was found to be approximately 1.06.

VI. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached:

1. The first cascade configuration of seven blades with aspect ratio of 1.25 and diffusion factor of 0.577 gave unsuitable flow conditions; the results were preliminary, however, because

   i) leakage around the blade ends resulted from a bowed plexiglass side wall,

   ii) the proper behavior of the inlet guide vanes with a metal screen attached, at the prescribed $\beta_1 = 60$ degrees, was not verified before the cascade blades were installed,

   iii) upstream and downstream probes were mounted together and there might have been interference on the downstream probe from the wake of the upstream probe.

2. The second cascade configuration of 15 blades with aspect ratio of 1.95 and diffusion factor of 0.394 gave excellent flow conditions. Specifically,

   i) static pressure was uniform at both upstream and downstream stations to $\pm 0.1''$ water,

   ii) impact pressure was periodic at the upstream measuring plane because of inlet guide vane wakes. The peak-to-peak variation was $\pm 4\%$ of dynamic pressure over two-inch intervals. The average of the periodic profile was almost constant in the blade-to-blade direction.

   iii) The flow angle at mid-span varied less than ± 0.5 degrees upstream and less than ± 0.75 degrees at the downstream

traversing plane.

iv) From rake and single survey probe results, the flow downstream was closely periodic over at least the four central blade passages.

v) The downstream flow was independent of spanwise location within ± 2 inches of the mid-span plane.

vi) The AVDR was about 1.06.

3. The mechanical adjustment procedures for the end walls, and the method adopted to set the geometry of the end walls through the cascade, worked well.

4. The data acquisition software and acquisition procedures were satisfactory, and will serve future studies conducted in the facility.

The following recommendations are made:

1. Analyze probe survey data to evaluate fully the blade element performance of the cascade (including mass-averaged total pressure loss coefficient, actual diffusion factor, and measured deviation angle).

2. Repeat measurement for a range of incidence angles.

3. Design and install a screen to eliminate guide vane wakes, and repeat blade element measurements.

4. Evaluate various flow visualization techniques.

5. Carry out experiments with blades instrumented with surface pressure taps, so that a momentum balance can be carried out on the mid-span measurements.

6. Evaluate the use of upstream side wall suction (for which the facility is designed) to reduce the boundary layer thickness and thereby control the AVDR and secondary flow effects.

TABLE I.

Cascade Configuration Data

	Configuration 1	Configuration 2
Blade type	NACA 65-series	C-series
Number of blades	7	15
Spacing (s) (inches)	8	4
Chord (c) (inches)	8.0	5.12
Solidity (σ)	1.0	1.28
Thickness (% chord)	10	13.5
Camber angle (φ)	36	20
Stagger angle (γ)	46.1	16.2
Air inlet angle (β_1)	60	39.8
Incidence angle (i)	-4.1	13.6
Deviation angle (δ)	11.5	6.6
Air outlet angle (β_2)	39.6	12.8
Diffusion factor (D)	0.577	0.394

(Last three values calculated by methods of Ref. 1)

Table II Rake Survey Data Downstream

```
REDUCED RAKE DATA FROM RAW DATA IN FILE RAW528
THIS REDUCED DATA STORED IN FILE RED528


POINT # 1        RAKE POSITION: 7.999
PLENUM PRESSURE: 17.68      PLENUM TEMP: 492.383
    AMBIENT PRESSURE: 411.893
TOTAL PRESSURES:
POSITION    Pt-Pa (inH2O)     S/V PORT
     .25       14.64             7
     .75       15.28             8
    1.50       15.24             9
    2.50       14.84            10
    3.50       14.89            12
    4.50       14.66            13
    5.50       14.66            14
    6.50       14.71            15
    7.50       14.79            17
    8.50       15.90            18
    9.25       15.53            19
    9.75       13.77            20
STATIC PRESSURES:
POSITION    Ps-Pa (inH2O)     S/V PORT
    0.00         .45             6
    3.00        1.75            11
    7.00        1.92            16
   10.00         .06            21


POINT # 2        RAKE POSITION: 6.997
PLENUM PRESSURE: 17.62      PLENUM TEMP: 492.383
    AMBIENT PRESSURE: 411.893
TOTAL PRESSURES:
POSITION    Pt-Pa (inH2O)     S/V PORT
     .25       13.48             7
     .75       14.33             8
    1.50       15.58             9
    2.50       16.71            10
    3.50       16.81            12
    4.50       16.86            13
    5.50       16.82            14
    6.50       16.87            15
    7.50       16.72            17
    8.50       16.10            18
    9.25       14.31            19
    9.75       12.60            20
STATIC PRESSURES:
POSITION    Ps-Pa (inH2O)     S/V PORT
    0.00         .61             6
    3.00        1.85            11
    7.00        2.24            16
   10.00         .06            21
```

POINT # 3 RAKE POSITION: 6.007
PLENUM PRESSURE: 17.68 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.348
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	9.16	7
.75	11.94	8
1.50	14.71	9
2.50	16.46	10
3.50	16.57	12
4.50	16.86	13
5.50	16.84	14
6.50	16.66	15
7.50	16.30	17
8.50	14.57	18
9.25	12.63	19
9.75	10.71	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.64	6
3.00	1.84	11
7.00	2.18	16
10.00	.11	21

POINT # 4 RAKE POSITION: 4.993
PLENUM PRESSURE: 17.73 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.348
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	8.24	7
.75	9.53	8
1.50	10.76	9
2.50	15.54	10
3.50	16.63	12
4.50	16.63	13
5.50	16.60	14
6.50	16.50	15
7.50	15.83	17
8.50	10.20	18
9.25	9.22	19
9.75	8.33	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.68	6
3.00	1.76	11
7.00	2.11	16
10.00	.02	21

POINT # 5 RAKE POSITION: 4.493
PLENUM PRESSURE: 17.82 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	10.70	7
.75	13.06	8
1.50	12.72	9
2.50	14.36	10
3.50	15.70	12
4.50	16.16	13
5.50	16.26	14
6.50	15.97	15
7.50	14.88	17
8.50	11.59	18
9.25	12.78	19
9.75	11.52	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.55	6
3.00	1.60	11
7.00	1.97	16
10.00	.13	21

POINT # 6 RAKE POSITION: 4.003
PLENUM PRESSURE: 17.71 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 412.165

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	12.96	7
.75	15.13	8
1.50	15.82	9
2.50	14.69	10
3.50	14.16	12
4.50	14.08	13
5.50	14.13	14
6.50	14.25	15
7.50	14.34	17
8.50	15.64	18
9.25	15.54	19
9.75	13.33	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.58	6
3.00	1.60	11
7.00	1.85	16
10.00	.10	21

POINT # 7 RAKE POSITION: 3.496
PLENUM PRESSURE: 17.77 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	12.89	7
.75	15.15	8
1.50	16.05	9
2.50	16.67	10
3.50	16.60	12
4.50	16.67	13
5.50	16.61	14
6.50	16.62	15
7.50	16.64	17
8.50	16.28	18
9.25	14.78	19
9.75	13.45	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.68	6
3.00	1.86	11
7.00	2.07	16
10.00	.08	21

POINT # 8 RAKE POSITION: 3.007
PLENUM PRESSURE: 17.76 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	12.52	7
.75	14.62	8
1.50	16.18	9
2.50	16.77	10
3.50	16.89	12
4.50	16.83	13
5.50	16.73	14
6.50	16.72	15
7.50	16.61	17
8.50	15.88	18
9.25	14.20	19
9.75	12.57	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.73	6
3.00	1.87	11
7.00	2.16	16
10.00	.03	21

POINT # 9 RAKE POSITION: 2.501
PLENUM PRESSURE: 17.71 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	11.17	7
.75	14.53	8
1.50	16.06	9
2.50	16.95	10
3.50	16.82	12
4.50	17.02	13
5.50	16.97	14
6.50	17.05	15
7.50	17.00	17
8.50	15.79	18
9.25	13.57	19
9.75	11.90	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.56	6
3.00	1.81	11
7.00	2.19	16
10.00	.18	21

POINT # 10 RAKE POSITION: 1.989
PLENUM PRESSURE: 17.72 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 412.029
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	9.11	7
.75	12.59	8
1.50	15.39	9
2.50	16.65	10
3.50	16.76	12
4.50	16.86	13
5.50	16.92	14
6.50	16.78	15
7.50	16.60	17
8.50	14.78	18
9.25	12.47	19
9.75	10.61	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.46	6
3.00	1.75	11
7.00	2.11	16
10.00	-.08	21

POINT # 11 RAKE POSITION: 1.494
PLENUM PRESSURE: 17.72 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	7.52	7
.75	10.01	8
1.50	15.16	9
2.50	16.60	10
3.50	16.59	12
4.50	16.62	13
5.50	16.57	14
6.50	16.60	15
7.50	16.26	17
8.50	12.05	18
9.25	9.97	19
9.75	8.61	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.48	6
3.00	1.82	11
7.00	2.07	16
10.00	-.10	21

POINT # 12 RAKE POSITION: .986
PLENUM PRESSURE: 17.75 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.485

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	9.82	7
.75	8.82	8
1.50	14.60	9
2.50	16.63	10
3.50	16.68	12
4.50	16.84	13
5.50	16.83	14
6.50	16.75	15
7.50	15.59	17
8.50	9.76	18
9.25	9.02	19
9.75	7.95	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.59	6
3.00	1.80	11
7.00	2.02	16
10.00	.18	21

POINT # 13 RAKE POSITION: .507
PLENUM PRESSURE: 17.68 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.893
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	13.31	7
.75	12.40	8
1.50	13.74	9
2.50	15.44	10
3.50	15.63	12
4.50	15.91	13
5.50	15.99	14
6.50	15.75	15
7.50	14.34	17
8.50	12.00	18
9.25	13.02	19
9.75	11.30	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.56	6
3.00	1.61	11
7.00	1.80	16
10.00	.13	21

POINT # 14 RAKE POSITION: .256
PLENUM PRESSURE: 17.71 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 412.029
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	14.77	7
.75	14.40	8
1.50	13.39	9
2.50	13.85	10
3.50	14.14	12
4.50	14.44	13
5.50	14.22	14
6.50	13.99	15
7.50	13.41	17
8.50	14.11	18
9.25	14.45	19
9.75	12.74	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.52	6
3.00	1.49	11
7.00	1.72	16
10.00	.20	21

POINT # 15 RAKE POSITION: .014
PLENUM PRESSURE: 17.74 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	14.15	7
.75	15.55	8
1.50	15.16	9
2.50	14.50	10
3.50	14.52	12
4.50	14.32	13
5.50	14.31	14
6.50	14.32	15
7.50	14.70	17
8.50	16.02	18
9.25	15.53	19
9.75	13.57	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.71	6
3.00	1.58	11
7.00	1.81	16
10.00	.10	21

POINT # 16 RAKE POSITION:-.245
PLENUM PRESSURE: 17.68 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.485
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	14.74	7
.75	15.13	8
1.50	15.83	9
2.50	16.24	10
3.50	16.25	12
4.50	16.01	13
5.50	16.08	14
6.50	16.12	15
7.50	16.38	17
8.50	16.49	18
9.25	15.30	19
9.75	13.70	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.50	6
3.00	1.64	11
7.00	1.89	16
10.00	-.01	21

POINT # 17 RAKE POSITION:-.495
PLENUM PRESSURE: 17.75 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	14.01	7
.75	14.84	8
1.50	15.84	9
2.50	16.46	10
3.50	16.51	12
4.50	16.53	13
5.50	16.45	14
6.50	16.50	15
7.50	16.60	17
8.50	16.14	18
9.25	14.82	19
9.75	13.18	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.51	6
3.00	1.76	11
7.00	2.00	16
10.00	-.13	21

POINT # 18 RAKE POSITION:-1.018
PLENUM PRESSURE: 17.76 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.348

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	12.41	7
.75	13.93	8
1.50	15.34	9
2.50	16.56	10
3.50	16.74	12
4.50	16.87	13
5.50	16.85	14
6.50	16.81	15
7.50	16.63	17
8.50	16.00	18
9.25	13.98	19
9.75	12.39	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.60	6
3.00	1.78	11
7.00	2.08	16
10.00	-.01	21

POINT # 19 RAKE POSITION:-1.5
PLENUM PRESSURE: 17.7 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	11.02	7
.75	13.30	8
1.50	14.78	9
2.50	16.12	10
3.50	16.84	12
4.50	16.98	13
5.50	16.94	14
6.50	17.01	15
7.50	16.58	17
8.50	15.47	18
9.25	13.69	19
9.75	11.70	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.53	6
3.00	1.70	11
7.00	2.02	16
10.00	-.14	21

POINT # 20 RAKE POSITION:-2.009
PLENUM PRESSURE: 17.7 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	9.99	7
.75	12.16	8
1.50	15.03	9
2.50	16.28	10
3.50	16.63	12
4.50	16.75	13
5.50	16.91	14
6.50	16.77	15
7.50	16.48	17
8.50	14.49	18
9.25	12.36	19
9.75	10.04	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.36	6
3.00	1.66	11
7.00	2.00	16
10.00	-.05	21

POINT # 21 RAKE POSITION:-2.495
PLENUM PRESSURE: 17.74 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 412.165
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	7.43	7
.75	9.78	8
1.50	13.13	9
2.50	16.03	10
3.50	16.53	12
4.50	16.58	13
5.50	16.60	14
6.50	16.65	15
7.50	16.38	17
8.50	12.20	18
9.25	10.03	19
9.75	7.85	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.44	6
3.00	1.66	11
7.00	2.03	16
10.00	-.10	21

POINT # 22 RAKE POSITION:-3.005
PLENUM PRESSURE: 17.75 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	8.15	7
.75	9.51	8
1.50	11.61	9
2.50	16.01	10
3.50	16.63	12
4.50	16.58	13
5.50	16.72	14
6.50	16.76	15
7.50	15.96	17
8.50	9.88	18
9.25	8.52	19
9.75	8.21	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.48	6
3.00	1.68	11
7.00	1.95	16
10.00	.11	21

POINT # 23 RAKE POSITION:-3.506
PLENUM PRESSURE: 17.76 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	11.85	7
.75	13.54	8
1.50	12.57	9
2.50	15.40	10
3.50	16.31	12
4.50	16.28	13
5.50	16.25	14
6.50	15.99	15
7.50	14.48	17
8.50	11.38	18
9.25	12.44	19
9.75	11.88	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.41	6
3.00	1.58	11
7.00	1.77	16
10.00	.03	21

POINT # 24 RAKE POSITION:-4.009
PLENUM PRESSURE: 17.73 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 412.165
TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	13.86	7
.75	15.43	8
1.50	15.98	9
2.50	14.29	10
3.50	13.96	12
4.50	14.10	13
5.50	14.00	14
6.50	14.05	15
7.50	14.25	17
8.50	15.72	18
9.25	15.56	19
9.75	13.53	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.44	6
3.00	1.40	11
7.00	1.71	16
10.00	-.04	21

```
POINT # 25                              RAKE POSITION:-4.511
PLENUM PRESSURE: 17.84     PLENUM TEMP: 492.383
    AMBIENT PRESSURE: 411.621
TOTAL PRESSURES:
POSITION     Pt-Pa (inH20)     S/V PORT
     .25         13.43             7
     .75         15.02             8
    1.50         16.41             9
    2.50         16.68            10
    3.50         16.57            12
    4.50         16.65            13
    5.50         16.54            14
    6.50         16.70            15
    7.50         16.75            17
    8.50         16.72            18
    9.25         15.34            19
    9.75         13.19            20
STATIC PRESSURES:
POSITION     Ps-Pa (inH20)     S/V PORT
    0.00           .61             6
    3.00          1.76            11
    7.00          2.03            16
   10.00           .06            21


POINT # 26                              RAKE POSITION:-5.002
PLENUM PRESSURE: 17.76     PLENUM TEMP: 492.383
    AMBIENT PRESSURE: 411.485
TOTAL PRESSURES:
POSITION     Pt-Pa (inH20)     S/V PORT
     .25         12.32             7
     .75         14.42             8
    1.50         16.20             9
    2.50         16.82            10
    3.50         16.77            12
    4.50         16.77            13
    5.50         16.78            14
    6.50         16.68            15
    7.50         16.75            17
    8.50         16.45            18
    9.25         14.82            19
    9.75         12.76            20
STATIC PRESSURES:
POSITION     Ps-Pa (inH20)     S/V PORT
    0.00           .50             6
    3.00          1.74            11
    7.00          1.98            16
   10.00          -.03            21
```

POINT # 27 RAKE POSITION:-6.003
PLENUM PRESSURE: 17.72 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.757

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	10.63	7
.75	13.75	8
1.50	15.80	9
2.50	16.66	10
3.50	16.82	12
4.50	16.95	13
5.50	16.93	14
6.50	16.96	15
7.50	16.93	17
8.50	15.42	18
9.25	13.21	19
9.75	10.85	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.48	6
3.00	1.66	11
7.00	2.08	16
10.00	.05	21

POINT # 28 RAKE POSITION:-6.992
PLENUM PRESSURE: 17.71 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.621

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	8.05	7
.75	8.04	8
1.50	12.74	9
2.50	16.42	10
3.50	16.66	12
4.50	16.82	13
5.50	16.78	14
6.50	16.71	15
7.50	16.44	17
8.50	10.64	18
9.25	9.41	19
9.75	7.81	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.58	6
3.00	1.72	11
7.00	2.04	16
10.00	-.08	21

POINT # 29 RAKE POSITION:-8.003
PLENUM PRESSURE: 17.69 PLENUM TEMP: 492.383
AMBIENT PRESSURE: 411.893

TOTAL PRESSURES:

POSITION	Pt-Pa (inH2O)	S/V PORT
.25	13.94	7
.75	15.31	8
1.50	15.28	9
2.50	14.58	10
3.50	14.07	12
4.50	14.06	13
5.50	14.01	14
6.50	13.99	15
7.50	14.14	17
8.50	15.64	18
9.25	15.64	19
9.75	13.39	20

STATIC PRESSURES:

POSITION	Ps-Pa (inH2O)	S/V PORT
0.00	.37	6
3.00	1.43	11
7.00	1.63	16
10.00	-.05	21

Table III

Survey Probe Data

DATA FROM FILE REDL88
BLADE TO BLADE TRAVERSE

LOWER PLANE

Point	Loc(in)	Q/Q1ref	Ps/Q1ref	Pt/Q1ref	X/Xref
1	-8.00	.9210	-.0000	.0821	.9603
2	-7.80	.9387	.0000	.0637	.9693
3	-7.60	.9720	-.0000	.0291	.9861
4	-7.40	.9854	.0000	.0152	.9928
5	-7.20	.9918	.0000	.0085	.9959
6	-7.00	.9909	-.0000	.0094	.9955
7	-6.80	1.0026	.0000	-.0027	1.0013
8	-6.60	.9806	-.0000	.0201	.9904
9	-6.40	.9647	.0000	.0367	.9825
10	-6.20	.9262	.0000	.0767	.9629
11	-6.00	.9179	.0000	.0852	.9587
12	-5.80	.9394	.0000	.0629	.9697
13	-5.60	.9685	.0000	.0327	.9844
14	-5.40	.9858	.0000	.0148	.9930
15	-5.20	.9910	-.0000	.0094	.9955
16	-5.00	.9879	-.0000	.0126	.9940
17	-4.80	.9905	-.0000	.0099	.9953
18	-4.60	.9745	-.0000	.0265	.9874
19	-4.40	.9564	-.0000	.0454	.9783
20	-4.20	.9293	.0000	.0734	.9645
21	-4.00	.9112	-.0000	.0922	.9552
22	-3.80	.9217	-.0000	.0814	.9606
23	-3.60	.9585	.0000	.0432	.9793
24	-3.40	.9839	.0000	.0167	.9920
25	-3.20	.9875	-.0000	.0130	.9938
26	-3.00	.9888	.0000	.0117	.9945
27	-2.80	.9867	-.0000	.0139	.9934
28	-2.60	.9862	.0000	.0144	.9932
29	-2.40	.9471	-.0000	.0550	.9736
30	-2.20	.9286	.0000	.0741	.9642
31	-2.00	.9143	-.0000	.0890	.9568
32	-1.80	.9377	-.0000	.0647	.9688
33	-1.60	.9730	.0000	.0281	.9866
34	-1.40	.9793	.0000	.0215	.9898
35	-1.20	.9836	-.0000	.0170	.9919
36	-1.00	.9857	-.0000	.0149	.9929
37	-.80	.9720	-.0000	.0291	.9861
38	-.60	.9634	.0000	.0381	.9818
39	-.40	.9491	.0000	.0529	.9746
40	-.20	.9183	-.0000	.0848	.9589
41	0.00	.9147	-.0000	.0886	.9570
42	.20	.9088	-.0000	.0947	.9540
43	.40	.9338	-.0000	.0688	.9668
44	.60	.9566	-.0000	.0451	.9784
45	.80	.9904	.0000	.0100	.9953
46	1.00	.9970	-.0000	.0032	.9985
47	1.20	.9875	-.0000	.0130	.9938
48	1.40	.9712	-.0000	.0299	.9857
49	1.60	.9635	-.0000	.0379	.9819
50	1.80	.9299	.0000	.0728	.9649

51	2.00	.9284	-.0000	.0743	.9641
52	2.20	.9403	.0000	.0621	.9701
53	2.40	.9704	.0000	.0308	.9853
54	2.60	.9863	.0000	.0143	.9932
55	2.80	1.0066	-.0000	-.0068	1.0032
56	3.00	.9733	.0000	.0278	.9868
57	3.20	.9841	.0000	.0165	.9922
58	3.40	.9691	.0000	.0321	.9847
59	3.60	.9451	-.0000	.0571	.9726
60	3.80	.9168	-.0000	.0865	.9531
61	4.00	.9295	.0000	.0732	.9646
62	4.20	.9467	-.0000	.0554	.9734
63	4.40	.9789	-.0000	.0220	.9895
64	4.60	.9863	-.0000	.0142	.9932
65	4.80	1.0017	.0000	-.0018	1.0009
66	5.00	.9909	-.0000	.0094	.9955
67	5.20	.9667	-.0000	.0347	.9834
68	5.40	.9740	.0000	.0270	.9871
69	5.60	.9323	.0000	.0704	.9661
70	5.80	.9231	-.0000	.0799	.9614
71	6.00	.9159	-.0000	.0873	.9577
72	6.20	.9475	-.0000	.0546	.9738
73	6.40	.9805	-.0000	.0203	.9903
74	6.60	.9824	.0000	.0182	.9913
75	6.80	.9913	-.0000	.0090	.9957
76	7.00	.9902	-.0000	.0102	.9951
77	7.20	.9918	.0000	.0085	.9960
78	7.40	.9805	-.0000	.0203	.9904
79	7.60	.9549	.0000	.0469	.9775
80	7.80	.9293	-.0000	.0734	.9645
81	8.00	.9379	.0000	.0645	.9689

DATA IN File L382

Record #1: Q/Qref
Record #2: Ps/Qref
Record #3: Pt/Qref
Record #4: X/Xref
Record #5: Positions

DATA FROM FILE U88M
BLADE TO BLADE TRAVERSE

UPPER PLANE

Point	Loc(in)	Q/Q1ref	Ps/Q1ref	Pt/Q1ref	X/Xref
1	-8.01	.6595	.2326	.0689	.8082
2	-7.91	.6256	.2876	.0987	.7872
3	-7.83	.6013	.2814	.1298	.7720
4	-7.72	.5779	.2780	.1571	.7571
5	-7.61	.5767	.2752	.1611	.7563
6	-7.52	.5825	.2784	.1519	.7601
7	-7.42	.5991	.2799	.1334	.7707
8	-7.32	.6281	.2831	.1006	.7889
9	-7.22	.6483	.2818	.0812	.8014
10	-7.13	.6595	.2791	.0725	.8082
11	-7.03	.6761	.2762	.0582	.8183
12	-6.84	.6856	.2772	.0476	.8239
13	-6.65	.6967	.2759	.0375	.8305
14	-6.46	.6994	.2746	.0360	.8321
15	-6.26	.7050	.2755	.0295	.8354
16	-6.05	.7084	.2738	.0276	.8374
17	-5.85	.7081	.2706	.0312	.8373
18	-5.66	.7086	.2717	.0297	.8375
19	-5.45	.7025	.2750	.0327	.8339
20	-5.25	.6962	.2763	.0378	.8302
21	-5.04	.6909	.2788	.0408	.8269
22	-4.84	.6878	.2770	.0458	.8252
23	-4.64	.6909	.2796	.0401	.8269
24	-4.44	.6988	.2773	.0343	.8316
25	-4.23	.6874	.2841	.0392	.8247
26	-4.13	.6651	.2886	.0576	.8113
27	-4.03	.6331	.2904	.0887	.7916
28	-3.93	.6031	.2897	.1201	.7729
29	-3.83	.5739	.2836	.1561	.7542
30	-3.63	.5676	.2820	.1641	.7501
31	-3.43	.6131	.2863	.1133	.7792
32	-3.24	.6586	.2834	.0696	.8074
33	-3.05	.6677	.2800	.0637	.8130
34	-2.82	.6707	.2768	.0637	.8149
35	-2.63	.6827	.2747	.0537	.8220
36	-2.43	.6879	.2772	.0458	.8251
37	-2.23	.6870	.2781	.0459	.8245
38	-2.03	.7027	.2778	.0300	.8338
39	-1.83	.6929	.2755	.0424	.8281
40	-1.62	.6930	.2790	.0387	.8281
41	-1.44	.6927	.2766	.0414	.8280
42	-1.23	.6829	.2803	.0479	.8221
43	-1.03	.6840	.2759	.0511	.8228
44	-.81	.6787	.2791	.0535	.8196
45	-.62	.6844	.2805	.0462	.8229
46	-.42	.6856	.2833	.0422	.8235
47	-.24	.6843	.2855	.0414	.8227
48	-.12	.6700	.2892	.0523	.8141
49	-.03	.6357	.2953	.0815	.7930

DATA IN File U88M1
Record #1: Q/Qref
Record #2: Ps/Qref
Record #3: Pt/Qref
Record #4: X/Xref

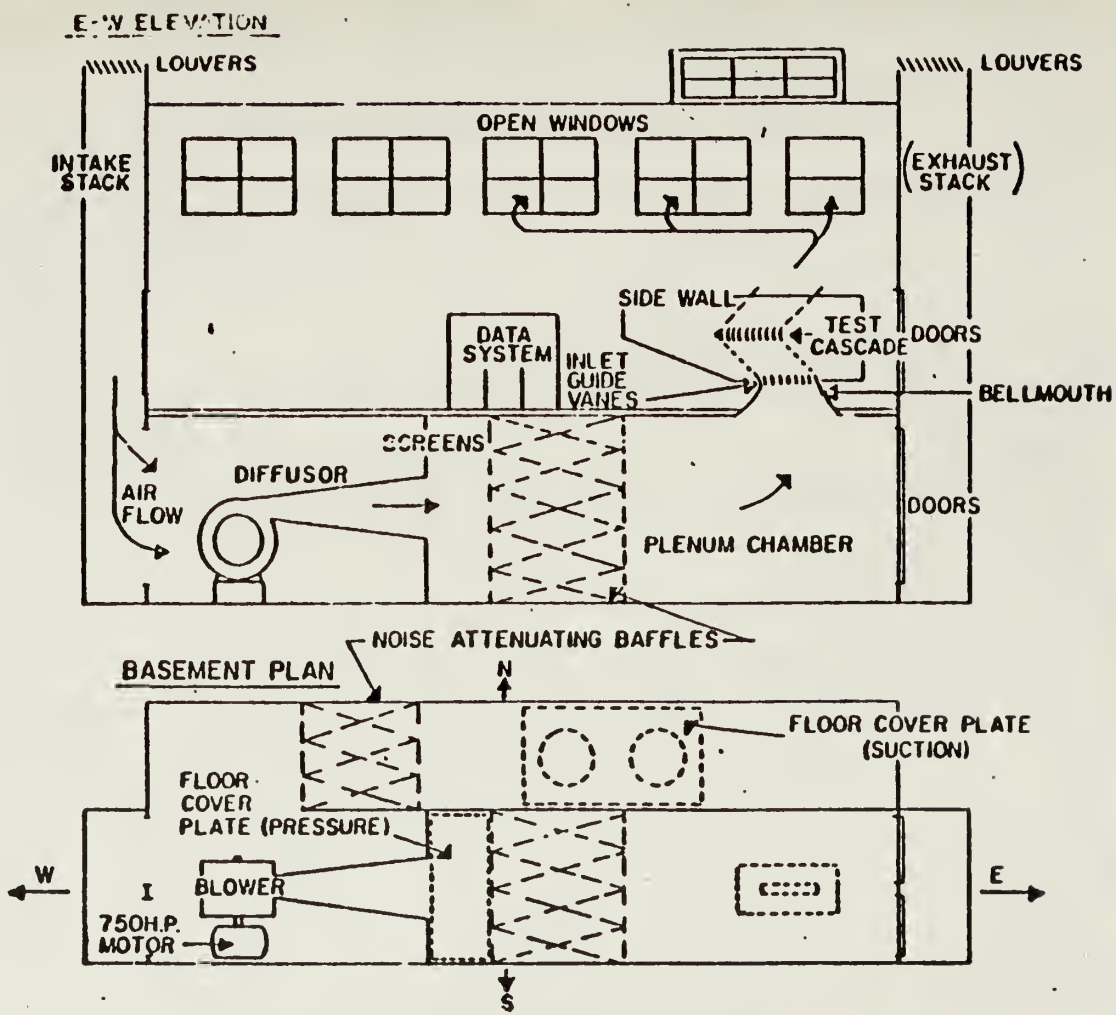
DATA FROM FILE U38P
BLADE TO BLADE TRAVERSE

UPPER PLANE

Point	Loc(in)	Q/Q1ref	Ps/Q1ref	Pt/Q1ref	X/Xref
1	.07	.6096	.2927	.1110	.7768
2	.16	.5835	.2908	.1397	.7601
3	.26	.5609	.2848	.1667	.7456
4	.37	.5666	.2840	.1637	.7493
5	.47	.5702	.2846	.1595	.7516
6	.57	.5901	.2887	.1349	.7644
7	.67	.6124	.2930	.1078	.7786
8	.78	.6398	.2911	.0816	.7956
9	.87	.6423	.2864	.0838	.7972
10	.96	.6598	.2825	.0697	.8080
11	1.15	.6611	.2844	.0664	.8088
12	1.34	.6696	.2824	.0597	.8140
13	1.54	.6784	.2830	.0500	.8192
14	1.74	.6783	.2838	.0495	.8191
15	1.93	.6891	.2800	.0420	.8256
16	2.14	.6835	.2836	.0444	.8222
17	2.35	.6866	.2822	.0425	.8241
18	2.55	.6839	.2788	.0485	.8226
19	2.75	.6826	.2822	.0466	.8217
20	2.96	.6839	.2841	.0433	.8224
21	3.14	.6861	.2830	.0421	.8238
22	3.35	.6936	.2820	.0355	.8282
23	3.55	.6867	.2886	.0360	.8240
24	3.76	.6702	.2981	.0433	.8140
25	3.86	.6512	.2980	.0631	.8024
26	3.96	.6129	.2975	.1029	.7787
27	4.06	.5842	.2919	.1377	.7606
28	4.15	.5648	.2831	.1665	.7482
29	4.26	.5590	.2857	.1699	.7443
30	4.36	.5684	.2879	.1581	.7504
31	4.49	.6053	.2872	.1209	.7742
32	4.60	.6295	.2890	.0943	.7893
33	4.68	.6390	.2875	.0860	.7952
34	4.80	.6518	.2908	.0696	.8030
35	4.89	.6677	.2816	.0624	.8128
36	5.08	.6751	.2836	.0528	.8172
37	5.28	.6834	.2789	.0490	.8223
38	5.48	.6885	.2809	.0417	.8253
39	5.68	.6920	.2820	.0372	.8273
40	5.87	.6884	.2839	.0389	.8251
41	6.08	.6890	.2806	.0415	.8255
42	6.26	.6813	.2829	.0472	.8209
43	6.47	.6861	.2817	.0434	.8238
44	6.67	.6802	.2788	.0524	.8204
45	6.86	.6752	.2826	.0538	.8173
46	7.06	.6787	.2856	.0472	.8193
47	7.26	.6831	.2830	.0452	.8220
48	7.45	.6862	.2831	.0420	.8238
49	7.65	.6852	.2904	.0356	.8231
50	7.74	.6746	.2927	.0443	.8167
51	7.86	.6486	.2970	.0667	.8009

DATA IN File U38P1
Record #1: Q/Qref
Record #2: Ps/Qref

Figure 1 Subsonic Cascade Facility



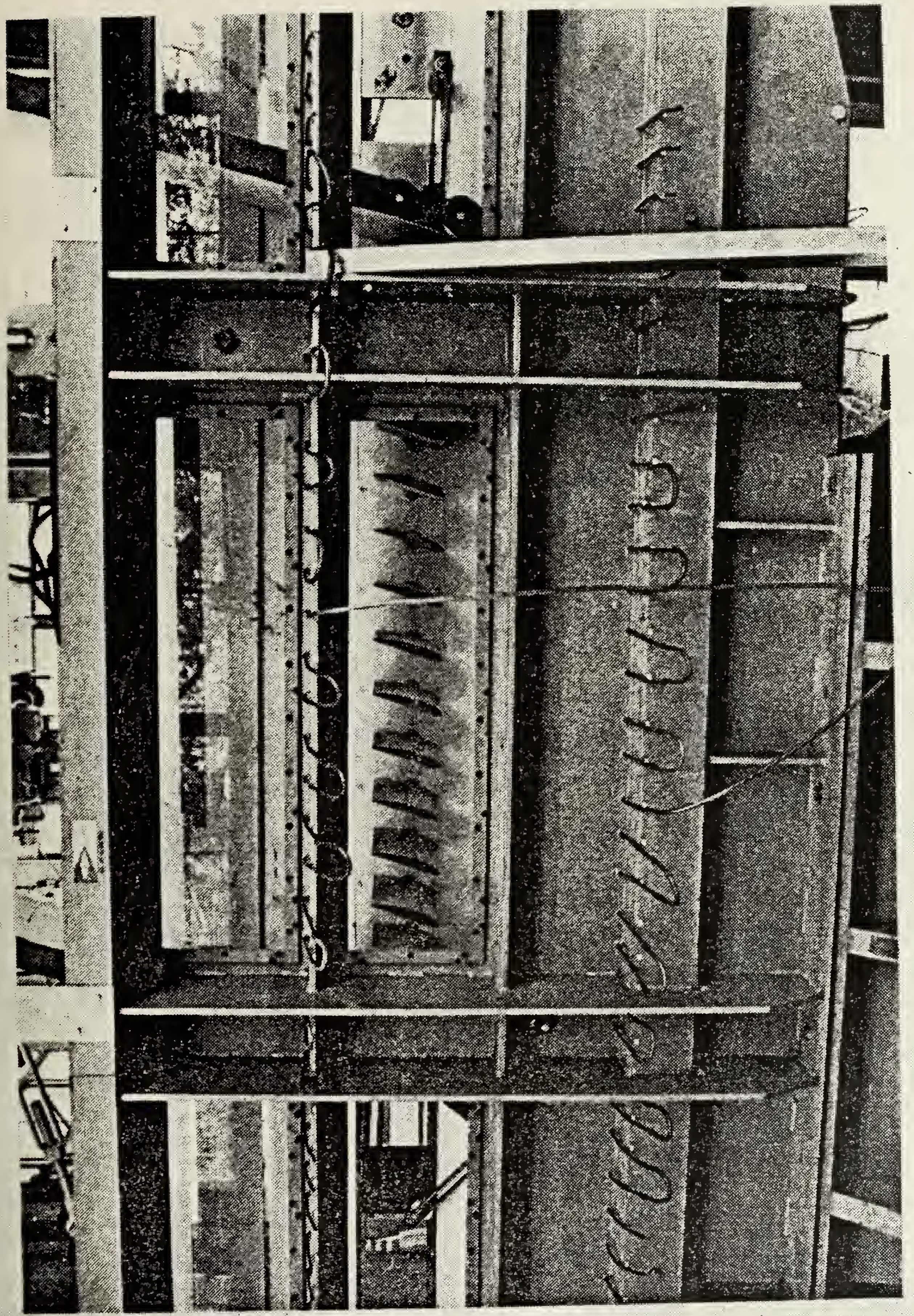


Figure 2 View of the Test Section

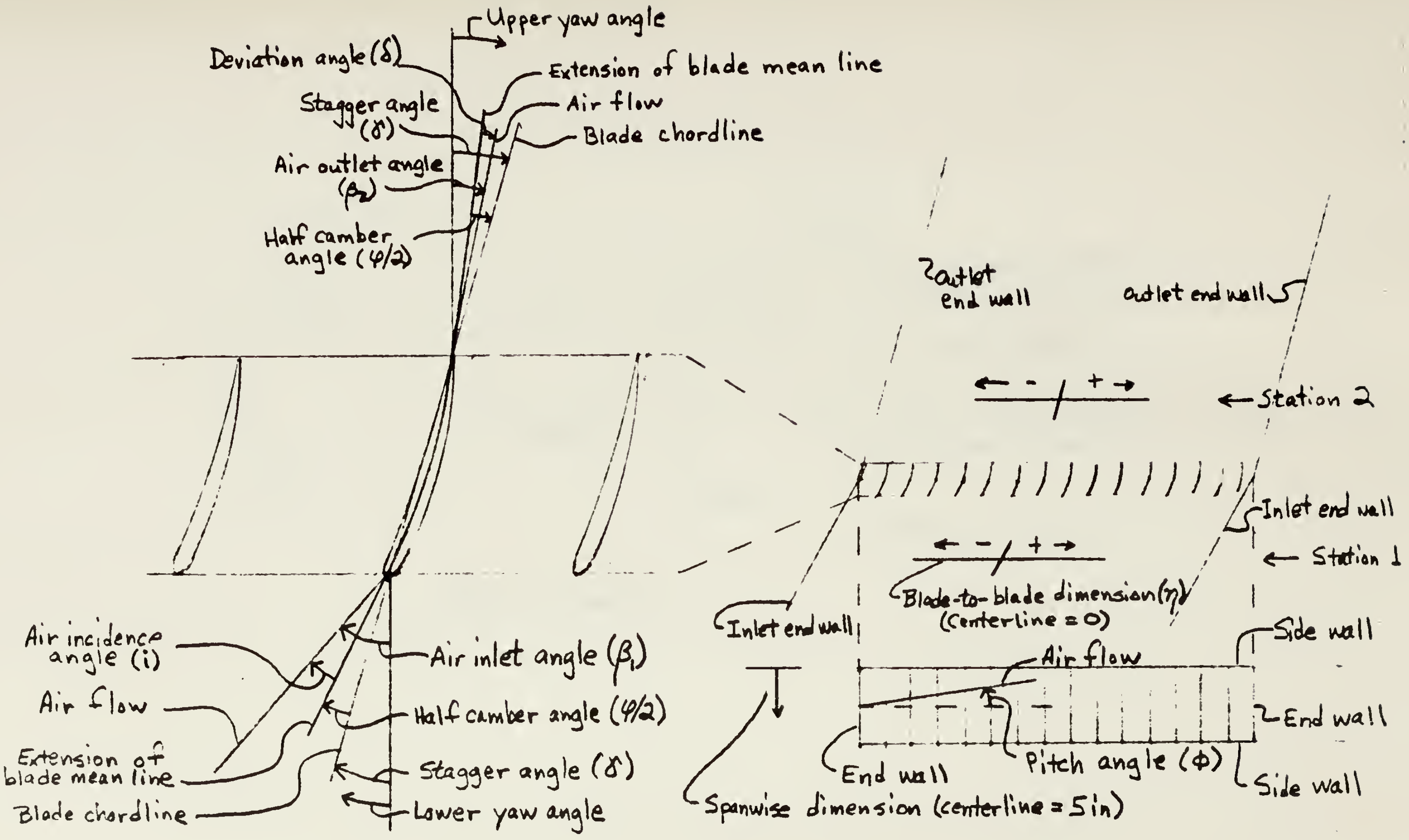


Figure 3 Cascade Terminology

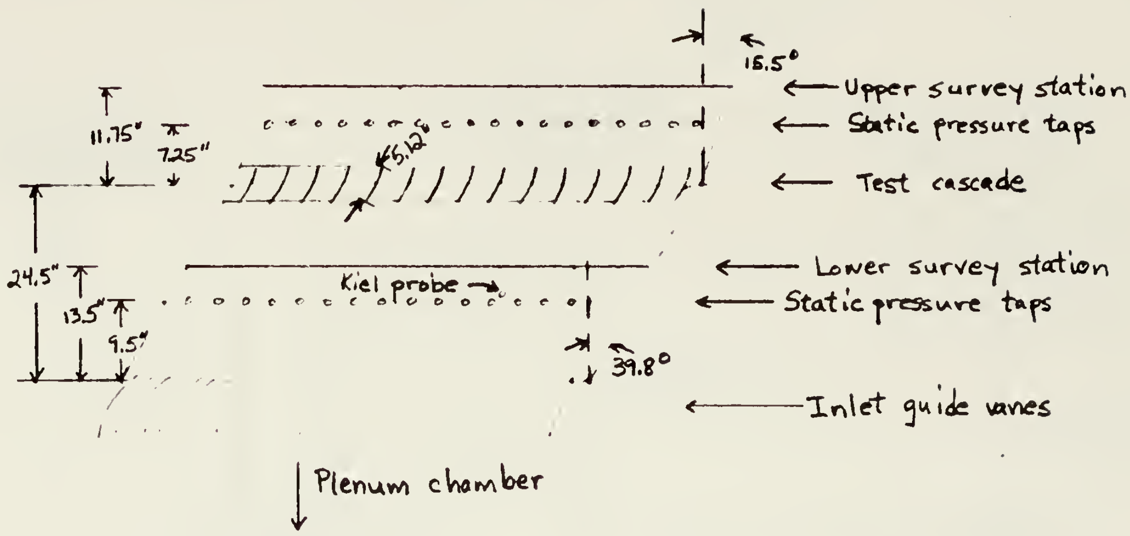


Figure 4 Instrumentation Layout

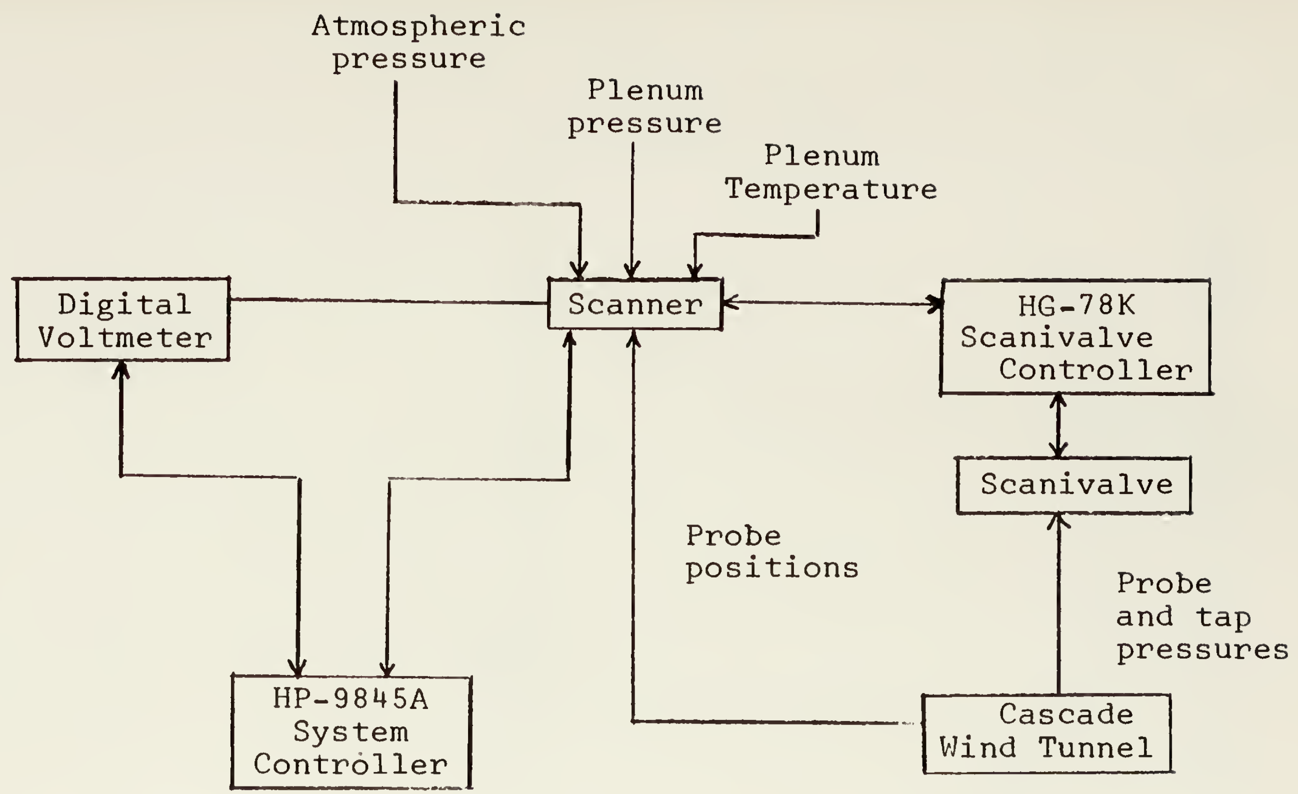


Figure 5 Data Acquisition System

Figure 6

Rake Impact Pressure Data at Upper Plane (Near Blade Suction Side)

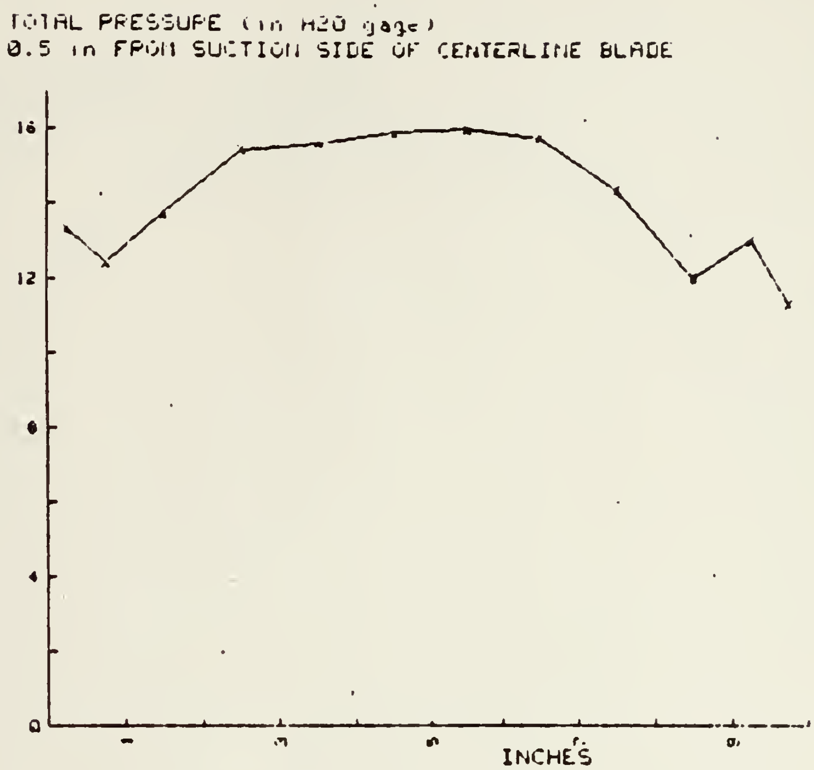


Figure 7

Rake Impact Pressure Data at Upper Plane (Near Mid-Span)

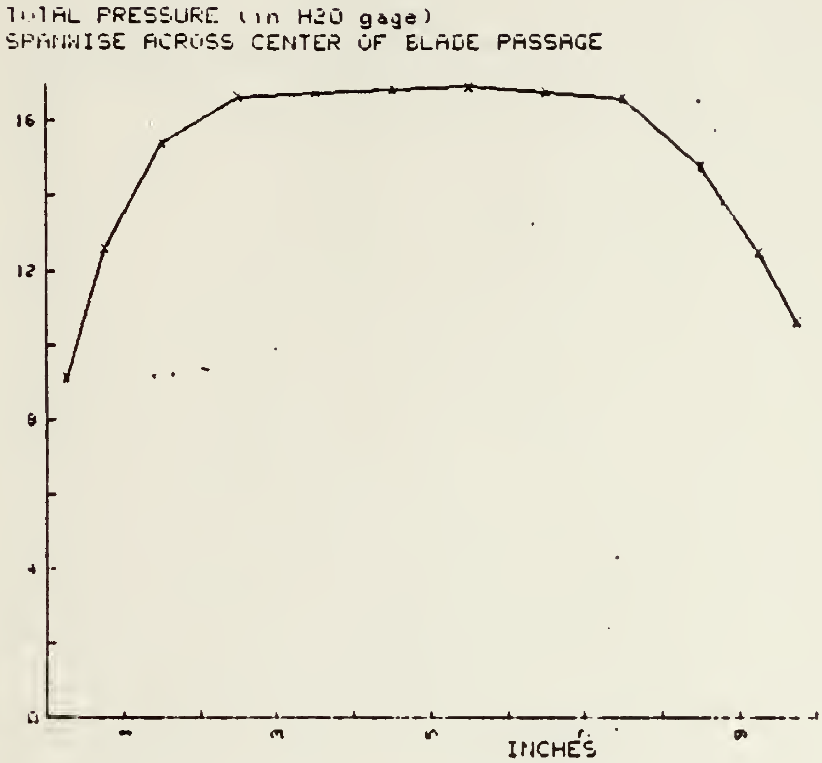


Figure 8

Rake Impact Pressure Data at Upper Plane (Near Pressure Side)

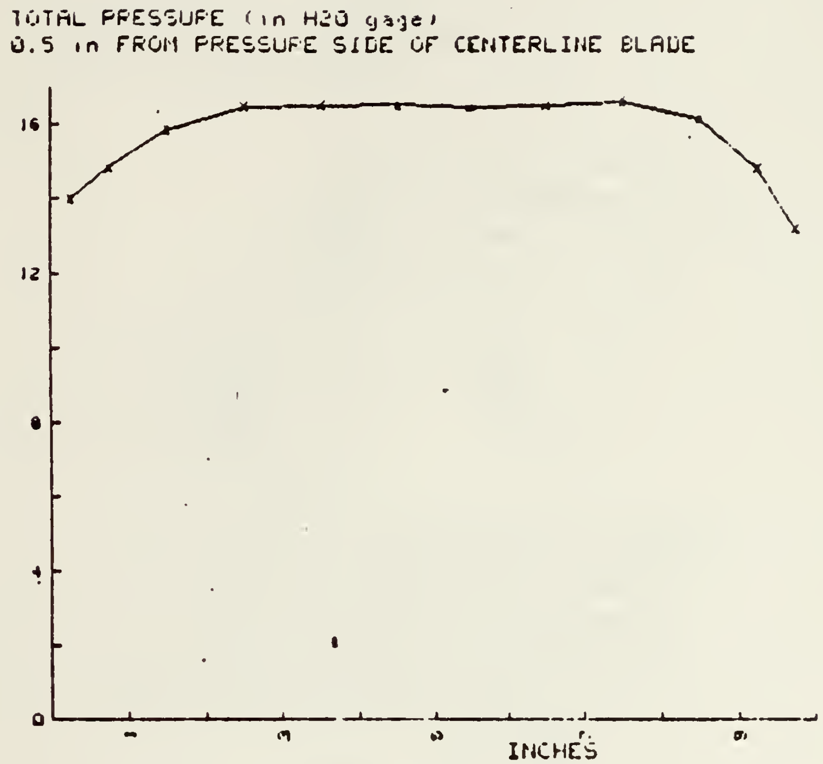


Figure 9

Rake Impact Pressure Data at Upper Plane (3-D Presentation)

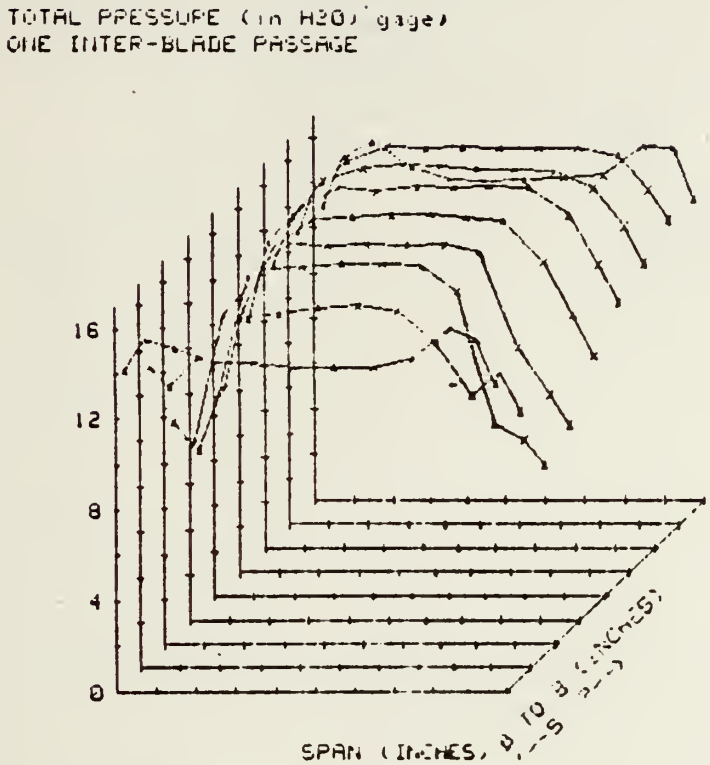


Figure 10

Rake Impact Pressure Data at Upper Plane

(0.5" from Suction Side of Three Blades)

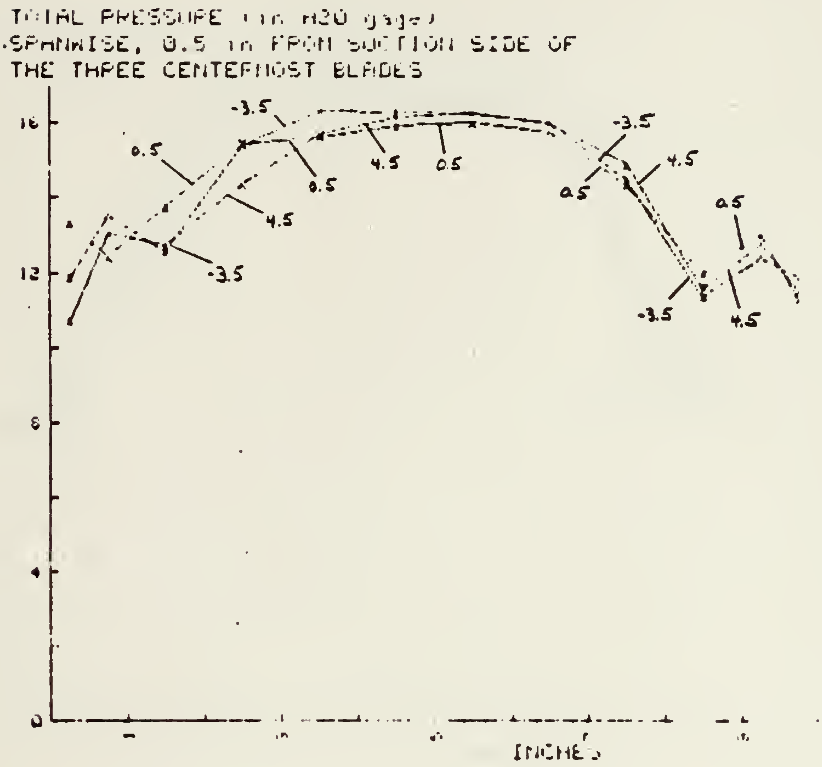


Figure 11

Rake Impact Pressure Data at Upper Plane
(1" from Suction Side of Four Blades)

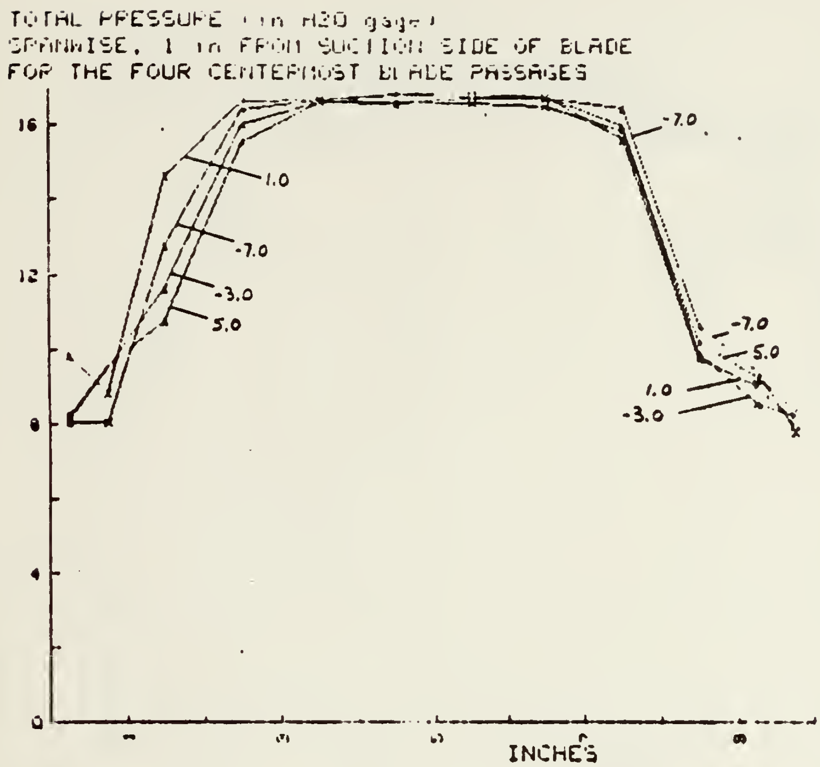


Figure 12

Rake Impact Pressure Data at Upper Plane
(Mid-Passage of Four Blades)

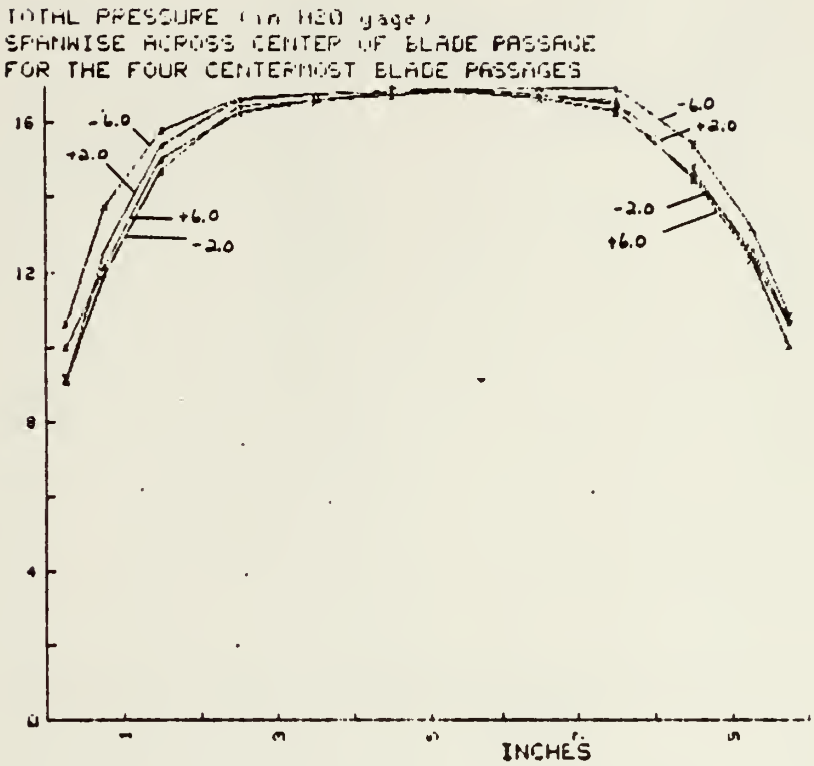
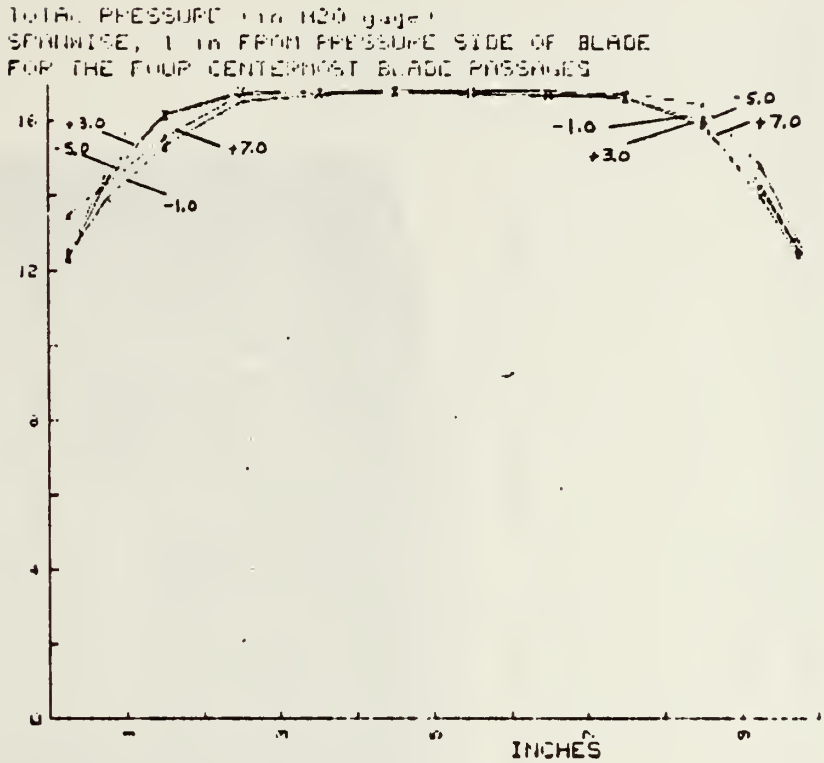
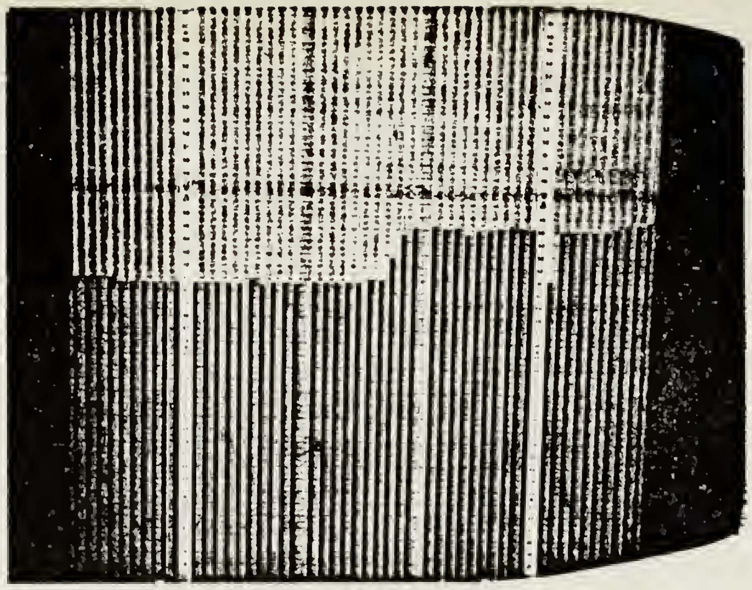


Figure 13

Rake Impact Pressure Data at Upper Plane

(1" from Pressure Side of Four Blades)





Left half--Outlet; Right half--Inlet

Figure 14

Side Wall Static Pressure Distributions at Upstream and Downstream Stations

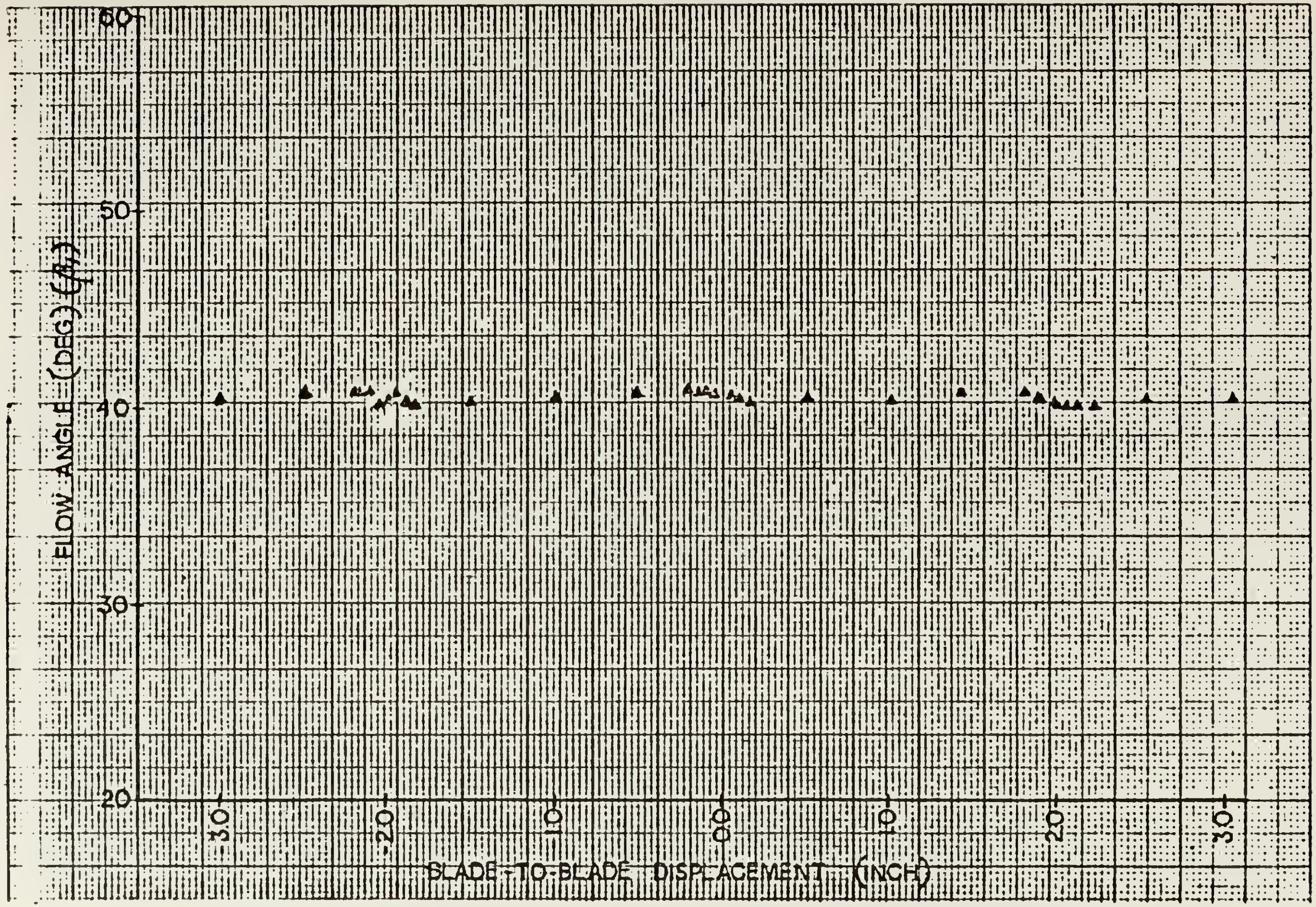


Figure 15. Probe Survey Data at Mid-Span (Flow Angle Upstream)

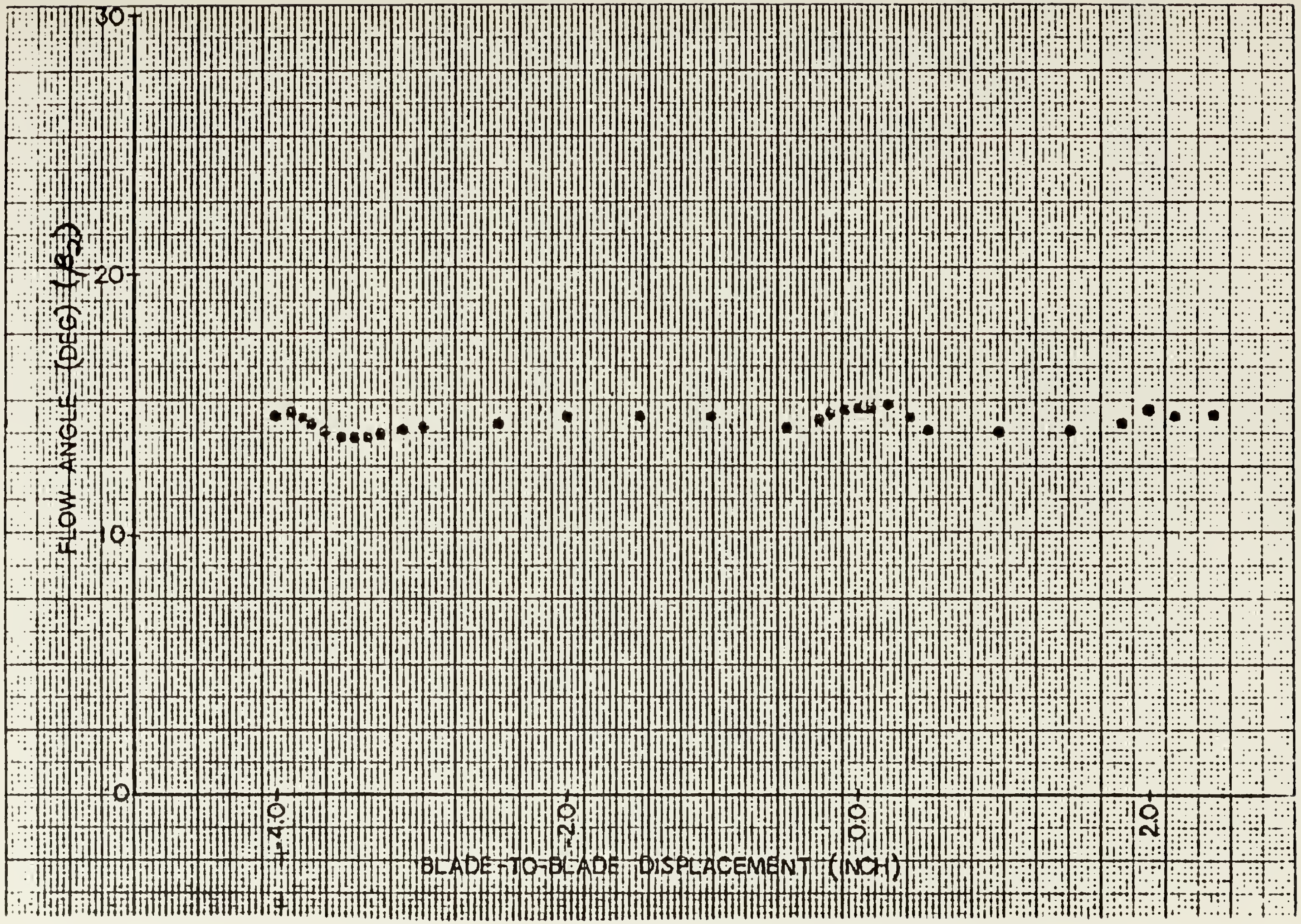


Figure 16. Probe Survey Data at Mid-Span (Flow Angle Downstream)

Figure 17

Probe Survey Data at Mid-Span ($(p_{kiel}-p_t)/Q_{ref}$ Downstream)

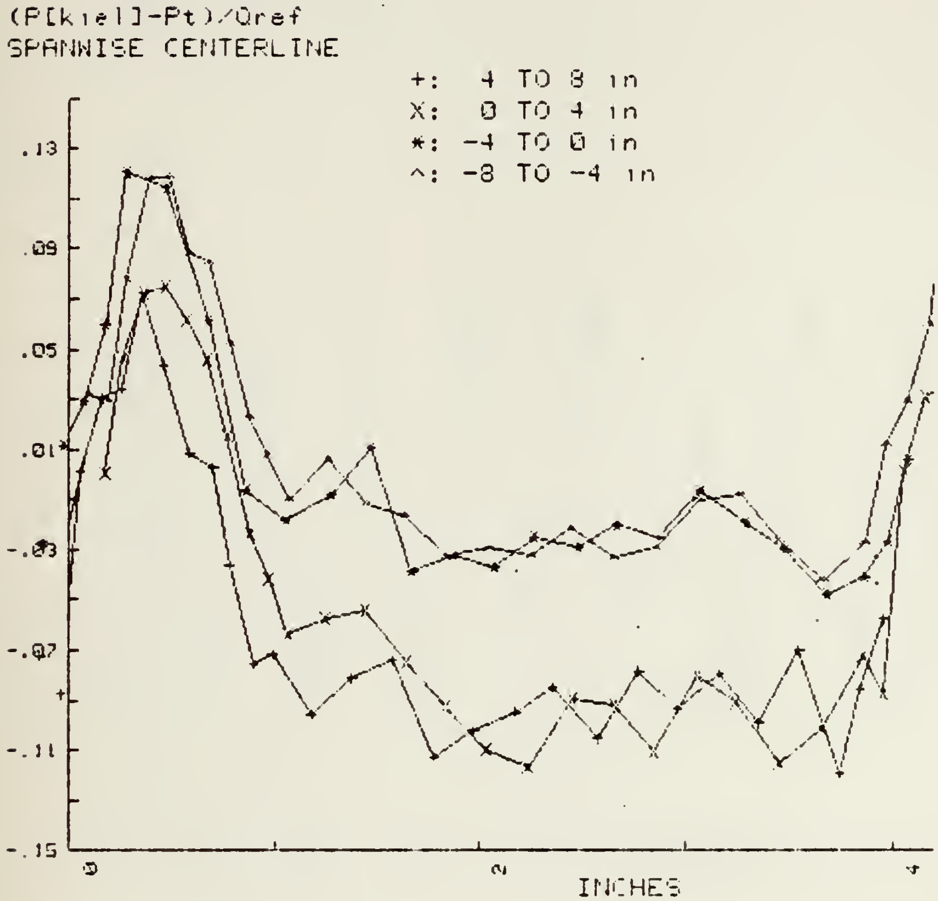


Figure 18

Probe Survey Data at Mid-Span $((p_{kiel}-p_t)/Q_{ref}$ Upstream)

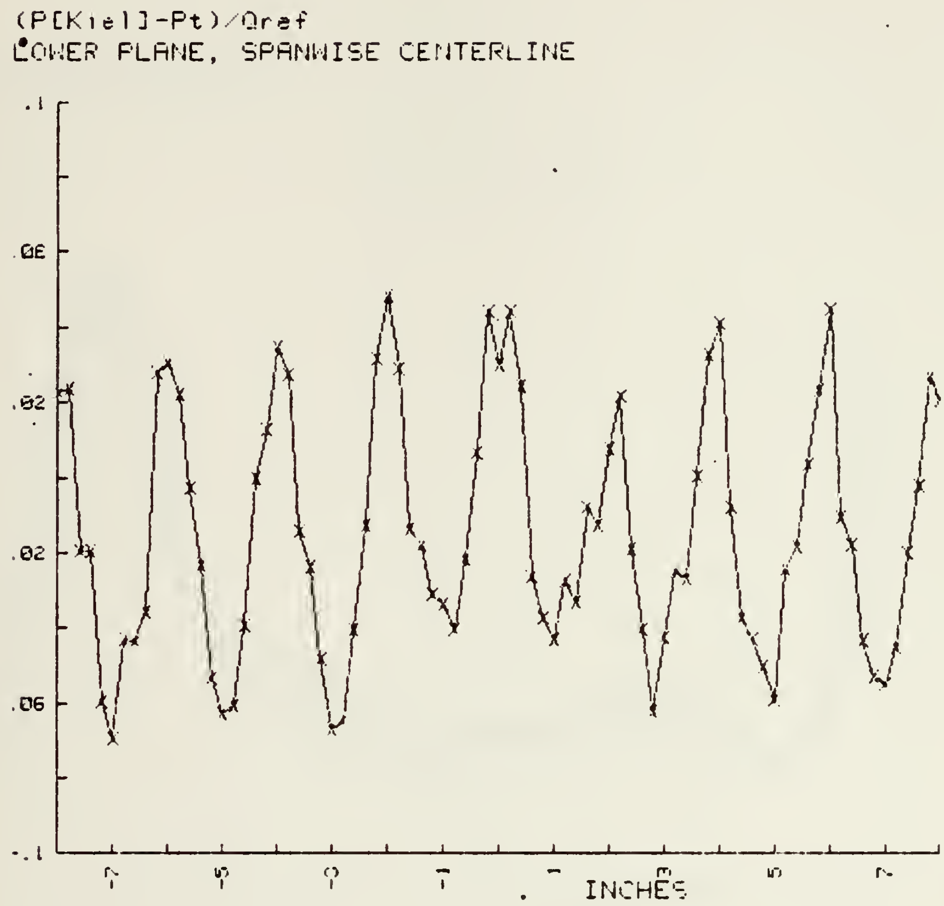


Figure 19

Probe Survey Data at Mid-Span ($(p_{plen}-p_t)/Q_{ref}$* Downstream)

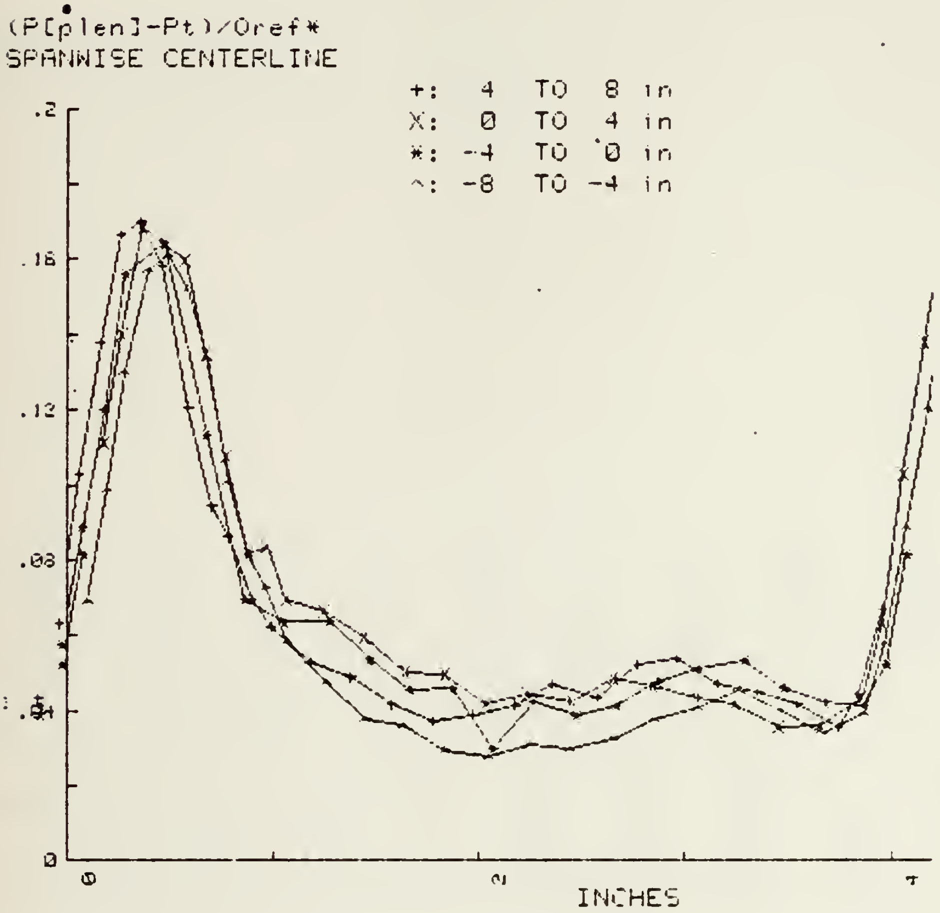


Figure 20

Probe Survey Data at Mid-Span ($(p_{plen}-p_t)/Q_{ref}^*$ Upstream)

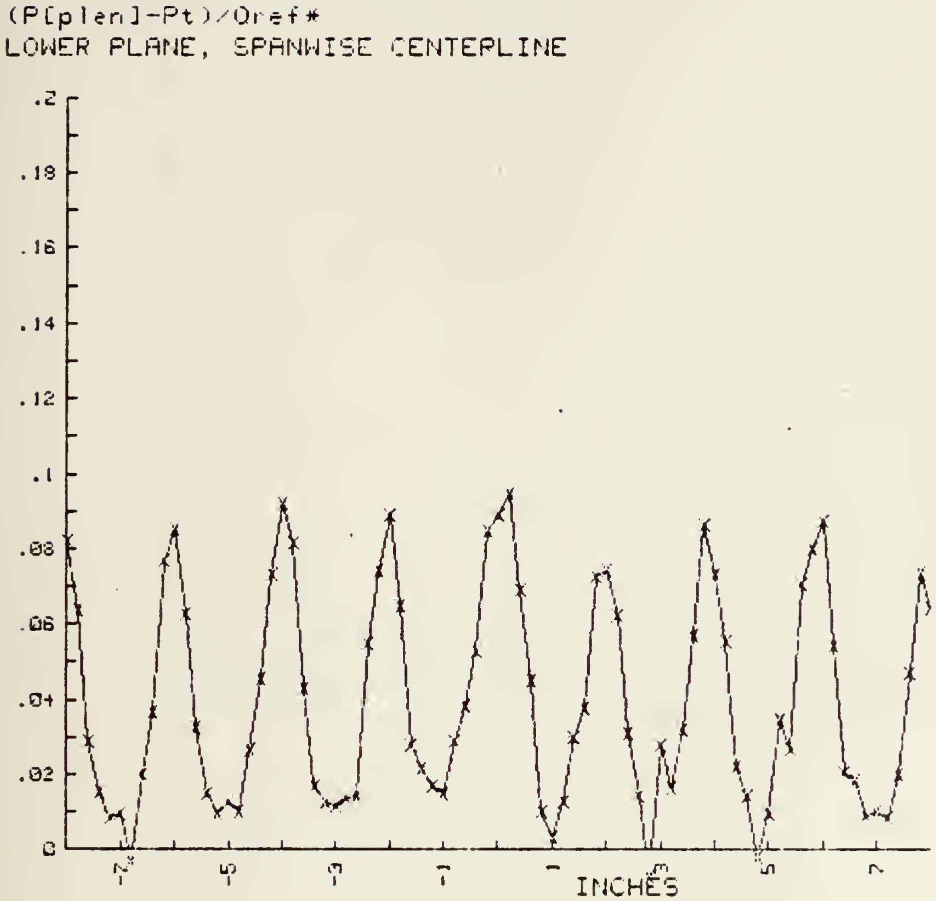
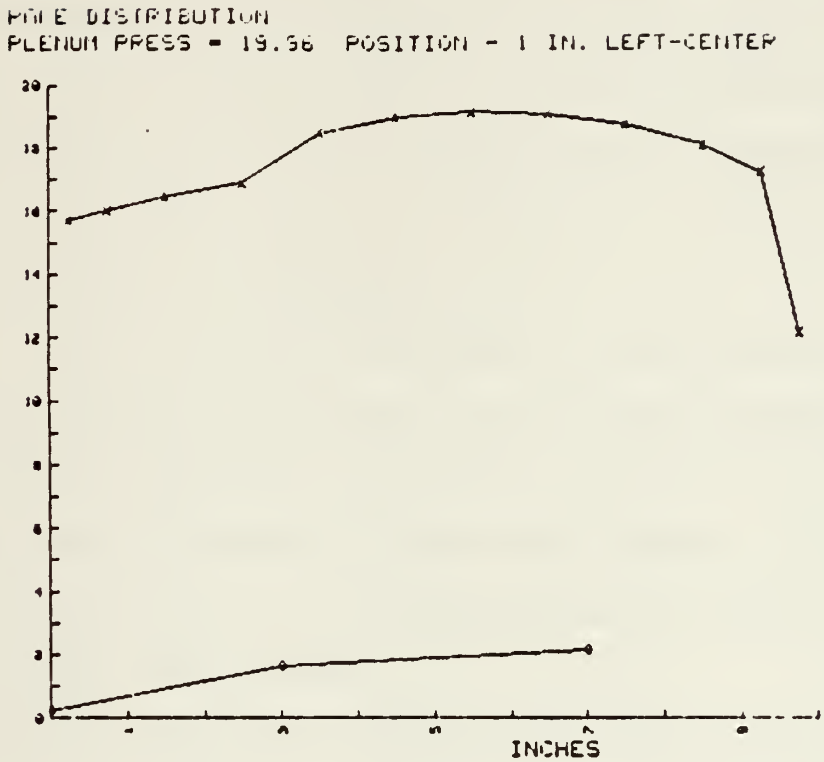


Figure 21

Rake Impact Pressure Data at Upper Plane
Blades Removed, Kiel Probe in Place



APPENDIX A: CASCADE TESTS WITH SEVEN NACA 65-SERIES BLADES

Seven NACA 65-series blades were installed at an air inlet angle (β_1) of 60 degrees and an air outlet angle (β_2) of 40 degrees. Measurements were made with five-hole probes at the inlet and outlet planes. Facility configuration and data acquisition were as described by Moebius [3].

Figures A-1 through A-4 show the measured pressure distributions, normalized to inlet dynamic pressure, at the outlet of a typical blade passage near the center of the cascade.

Figure A-1 shows the spanwise distribution of total pressure at five blade-to-blade positions in the passage. The data are presented as the difference between total pressure at the Kiel probe and total pressure at the traversing probe, normalized to inlet dynamic pressure. It can be seen that the flow was found not to be two-dimensional, since there is no spanwise area of uniform total pressure.

Figure A-2 shows the spanwise distribution of dynamic pressure at the four positions. Data are presented as dynamic pressure at the traversing probe normalized to inlet dynamic pressure. The figure shows a qualitatively similar behavior, with no region of two-dimensional conditions.

Figures A-3 and A-4 show the total and dynamic pressure distributions, respectively, as a three-dimensional picture of a blade passage. The distorted and unsatisfactory nature of the outlet flow can be seen in these figures.

Data from which Figures A-1 through A-4 were generated are listed in Table A.I.

Table A-I

First Configuration Probe Survey Data

RUN NO. 13

DATE 13 2 80

SPAN TRAVERSE

UPPER PLANE Directly downstream of blade trailing edge

LOC(IN)	Q/Q1REF	PS/Q1REF	PT/Q1REF	X/XREF
0.49	0.2817	0.4085	0.2921	0.5274
0.98	0.2906	0.4119	0.2798	0.5355
1.50	0.3417	0.4136	0.2263	0.5805
1.98	0.3898	0.4181	0.1732	0.6197
2.49	0.4578	0.4253	0.0968	0.6711
3.00	0.4721	0.4251	0.0824	0.6815
3.50	0.4460	0.4203	0.1137	0.6625
4.00	0.4127	0.4186	0.1492	0.6375
4.50	0.3942	0.4138	0.1729	0.6232
4.99	0.3905	0.4086	0.1819	0.6203
5.50	0.4030	0.4049	0.1728	0.6302
6.00	0.3986	0.4033	0.1789	0.6267
6.50	0.4293	0.4025	0.1484	0.6503
7.00	0.4397	0.4051	0.1353	0.6580
7.50	0.4502	0.4118	0.1179	0.6657
8.00	0.4464	0.4128	0.1207	0.6628
8.49	0.4545	0.4122	0.1131	0.6688
8.99	0.4563	0.4120	0.1116	0.6701
9.50	0.4436	0.4156	0.1209	0.6608

Q/QREF IN FILE Q13U
PS/QREF IN FILE PS13U
PT/QREF IN FILE PT13U
X/XREF IN FILE X13U
POSITIONS IN FILE POS13

RUN NO. 14

DATE 20 2 80

SPAN TRAVERSE

UPPER PLANE One inch from suction side

LOC(IN)	Q/Q1REF	PS/Q1REF	PT/Q1REF	X/XREF
0.49	0.1614	0.4057	0.4163	0.3993
0.99	0.2225	0.4097	0.3508	0.4685
1.49	0.3509	0.4174	0.2130	0.5875
1.99	0.4898	0.4219	0.0672	0.6932
2.50	0.5195	0.4220	0.0367	0.7137
3.00	0.4771	0.4224	0.0797	0.6842
3.50	0.4134	0.4191	0.1479	0.6372
4.00	0.3672	0.4127	0.2013	0.6009
4.50	0.3381	0.4075	0.2360	0.5769
5.00	0.3112	0.4027	0.2681	0.5536
5.51	0.3025	0.3996	0.2801	0.5459
6.00	0.2989	0.3936	0.2896	0.5428
6.50	0.3166	0.3918	0.2736	0.5585
7.00	0.3282	0.3905	0.2631	0.5686
7.50	0.3166	0.3930	0.2724	0.5584
8.00	0.2963	0.3940	0.2920	0.5403
8.50	0.2951	0.3947	0.2925	0.5392
9.00	0.3172	0.3968	0.2679	0.5589
9.50	0.3213	0.3981	0.2625	0.5625

Q/QREF IN FILE Q14U
PS/QREF IN FILE PS14U
PT/QREF IN FILE PT14U
X/XREF IN FILE X14U
POSITIONS IN FILE POS14

RUN NO. 15

DATE 20 2 80

SPAN TRAVERSE

UPPER PLANE Two inches from suction side

LOC(IN)	Q/Q1REF	PS/Q1REF	PT/Q1REF	X/XREF
0.50	0.3007	0.4055	0.2760	0.5449
1.00	0.3027	0.4032	0.2763	0.5466
1.50	0.4027	0.4113	0.1667	0.6298
1.99	0.5208	0.4119	0.0377	0.7209
2.49	0.5353	0.4164	0.0266	0.7254
2.99	0.4822	0.4166	0.0806	0.6886
3.49	0.4524	0.4150	0.1125	0.6672
3.98	0.4246	0.4075	0.1483	0.6466
4.49	0.3697	0.3978	0.2137	0.6038
4.98	0.3046	0.3878	0.2896	0.5486
5.48	0.2659	0.3891	0.3275	0.5126
5.99	0.2271	0.3808	0.3749	0.4740
6.49	0.2117	0.3797	0.3916	0.4577
6.99	0.2094	0.3762	0.3974	0.4553
7.49	0.2215	0.3795	0.3819	0.4681
7.98	0.2113	0.3876	0.3841	0.4571
8.48	0.1427	0.3937	0.4501	0.3758
8.99	0.1631	0.3888	0.4314	0.4019
9.49	0.2413	0.3892	0.3521	0.4884

Q/QREF IN FILE Q15U
PS/QREF IN FILE PS15U
PT/QREF IN FILE PT15U
X/XREF IN FILE X15U
POSITIONS IN FILE POS15

First Configuration Probe Survey Data (Continued)

RUN NO. 16

DATE 20 2 80

SPAN TRAVERSE

UPPER PLANE Four inches from suction side

LOC(IN)	Q/Q1REF	PS/Q1REF	PT/Q1REF	X/XREF
0.50	0.2725	0.4053	0.3047	0.5187
1.00	0.2761	0.4068	0.2995	0.5220
1.50	0.3860	0.4114	0.1835	0.6167
2.00	0.4936	0.4198	0.0658	0.6967
2.50	0.5764	0.4256	-0.0246	0.7522
3.00	0.5605	0.4263	-0.0091	0.7418
3.50	0.5453	0.4278	0.0050	0.7318
4.00	0.5381	0.4297	0.0104	0.7270
4.50	0.5216	0.4288	0.0281	0.7158
5.00	0.5037	0.4303	0.0449	0.7035
5.50	0.4743	0.4259	0.0794	0.6828
6.00	0.4580	0.4222	0.0996	0.6712
6.50	0.4367	0.4238	0.1197	0.6555
7.00	0.3909	0.4201	0.1699	0.6204
7.50	0.3146	0.4099	0.2574	0.5571
8.00	0.2601	0.4057	0.3167	0.5068
8.50	0.2082	0.4028	0.3720	0.4536
9.00	0.1673	0.4031	0.4129	0.4068
9.50	0.1396	0.4118	0.4321	0.3716

Q/QREF IN FILE Q16U
PS/QREF IN FILE PS16U
PT/QREF IN FILE PT16U
X/XREF IN FILE X16U
POSITIONS IN FILE POS16

RUN NO. 17

DATE 20 2 80

SPAN TRAVERSE

UPPER PLANE Seven inches from suction side
(One inch from pressure side)

LOC(IN)	Q/Q1REF	PS/Q1REF	PT/Q1REF	X/XREF
0.50	0.3853	0.4200	0.1757	0.6159
1.00	0.5349	0.4243	0.0191	0.7249
1.50	0.5663	0.4218	-0.0105	0.7458
2.00	0.5430	0.4251	0.0101	0.7304
2.50	0.5058	0.4290	0.0441	0.7049
3.00	0.4996	0.4304	0.0490	0.7006
3.50	0.5105	0.4408	0.0277	0.7081
4.00	0.5145	0.4361	0.0281	0.7108
4.50	0.5228	0.4380	0.0178	0.7165
5.00	0.5252	0.4392	0.0140	0.7181
5.50	0.5205	0.4426	0.0155	0.7148
6.00	0.5194	0.4411	0.0182	0.7140
6.50	0.5071	0.4380	0.0337	0.7056
7.00	0.5220	0.4394	0.0182	0.7159
7.50	0.5104	0.4722	0.0022	0.7090
8.00	0.5047	0.4413	0.0329	0.7040
8.50	0.5001	0.4365	0.0474	0.7003
9.00	0.4902	0.4403	0.0467	0.6939
9.50	0.4801	0.4372	0.0621	0.6868

Q/QREF IN FILE Q17U
PS/QREF IN FILE PS17U
PT/QREF IN FILE PT17U
X/XREF IN FILE X17U
POSITIONS IN FILE POS17

Figure A-1

First Configuration Results ($(p_{kiel}-p_t)/Q_{ref}$ Downstream)

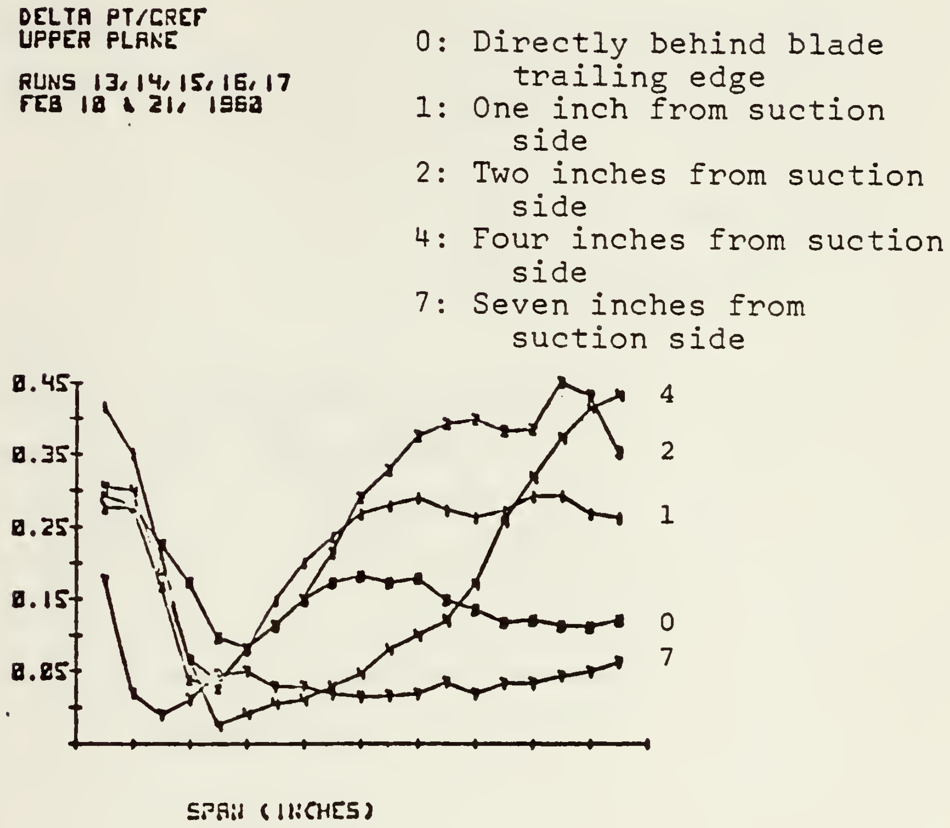


Figure A-2

First Configuration Results (Q/Q_{ref} Downstream)

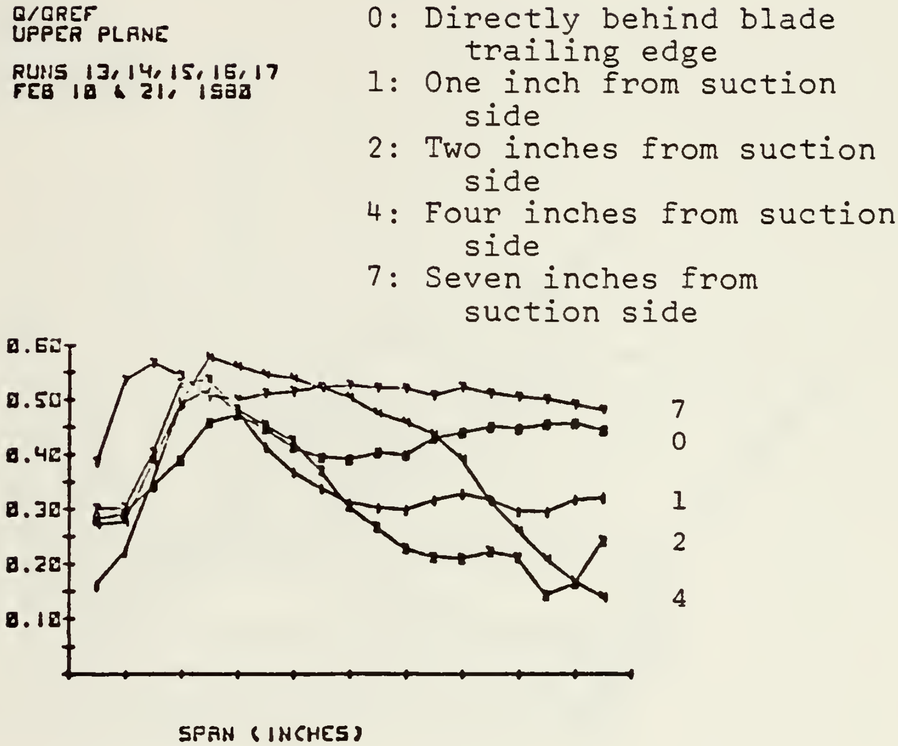


Figure A-3

First Configuration Results $((p_{kiel}-p_t)/Q_{ref}$ Downstream, 3-D)

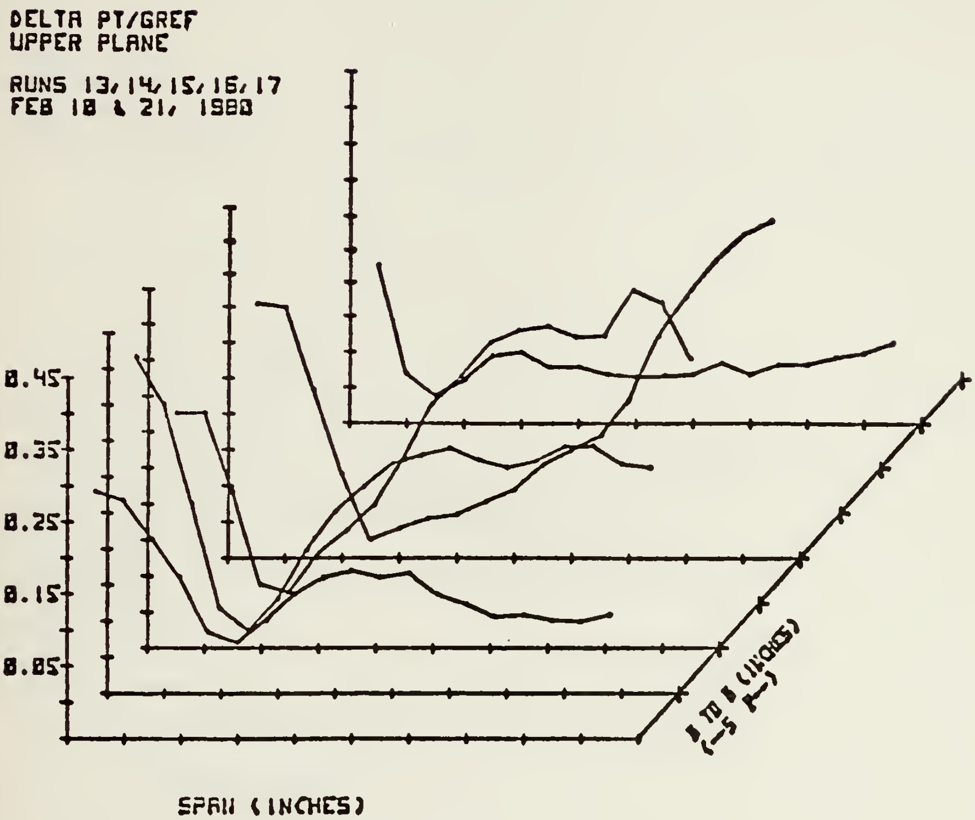
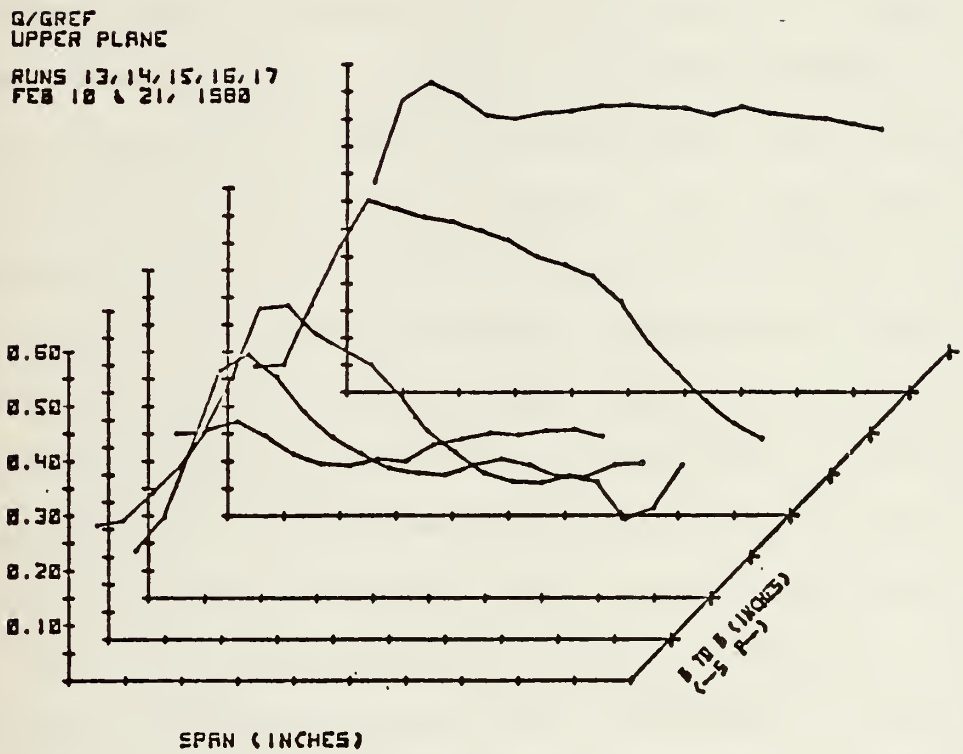


Figure A-4

First Configuration Results (Q/Q_{ref} Downstream, 3-D)



APPENDIX B: FIVE-SENSOR FLOW SURVEY PRESSURE PROBES

Two types of five-hole probes were used as traversing probes. The United Sensor Corporation DC-125-24-F-22-CD Probe, serial no. A981-2 (Fig. B-1) was used at the outlet plane. The United Sensor Corp. DA-125 Probe, serial no. A847-1 (Fig. B-2) was used at the inlet plane. While the probes differ in appearance, they were calibrated and used in a similar way.

Each probe has five pressure ports. When the probe is aligned with the flow, port number 1 senses an indication of the total pressure. The other four holes are arranged in pairs on opposite sides of the total pressure port, and are at an angle to the air stream. Ports 2 and 3 are in the same blade-to-blade plane, as the probe is rotated about its shaft. Ports 4 and 5 are separated in the spanwise direction. The probe was inserted into the airstream through a slot in the side wall. Before the reading of each data point, the probe was first rotated about its axis (the test section spanwise axis) until the pressures sensed by ports 2 and 3 were equal. The probe was then assumed to be aligned with the flow in the blade-to-blade plane. Through the calibration procedure given in Reference 10, the pressures sensed by the five ports were used to calculate the pitch angle (ϕ) (in the spanwise plane) and velocity (in relation to the "limiting velocity", $V/V_t = X$) of the flow at the probe.

A reference inlet dynamic pressure was used to normalize pressure data reported in Appendix A. The reference pressure was computed from the total pressure measured by the Kiel probe and the static pressure measured by the wall static tap near the inlet plane. These pressures were used to calculate a Mach number and a corresponding dynamic pressure. Before traverse

data were taken, the tunnel was run at slightly varying speeds (near the normal operating speed) with the lower traversing probe in the center of the inlet plane. A linear relationship was established between the dynamic pressure measured by the traversing probe and that computed from Kiel and wall static pressures as described above. The linear relation was applied to the measure of (fixed position) Kiel probe dynamic pressure for each data point, to calculate the reference inlet dynamic pressure for that point.

Figure B-1

Downstream Survey Probe

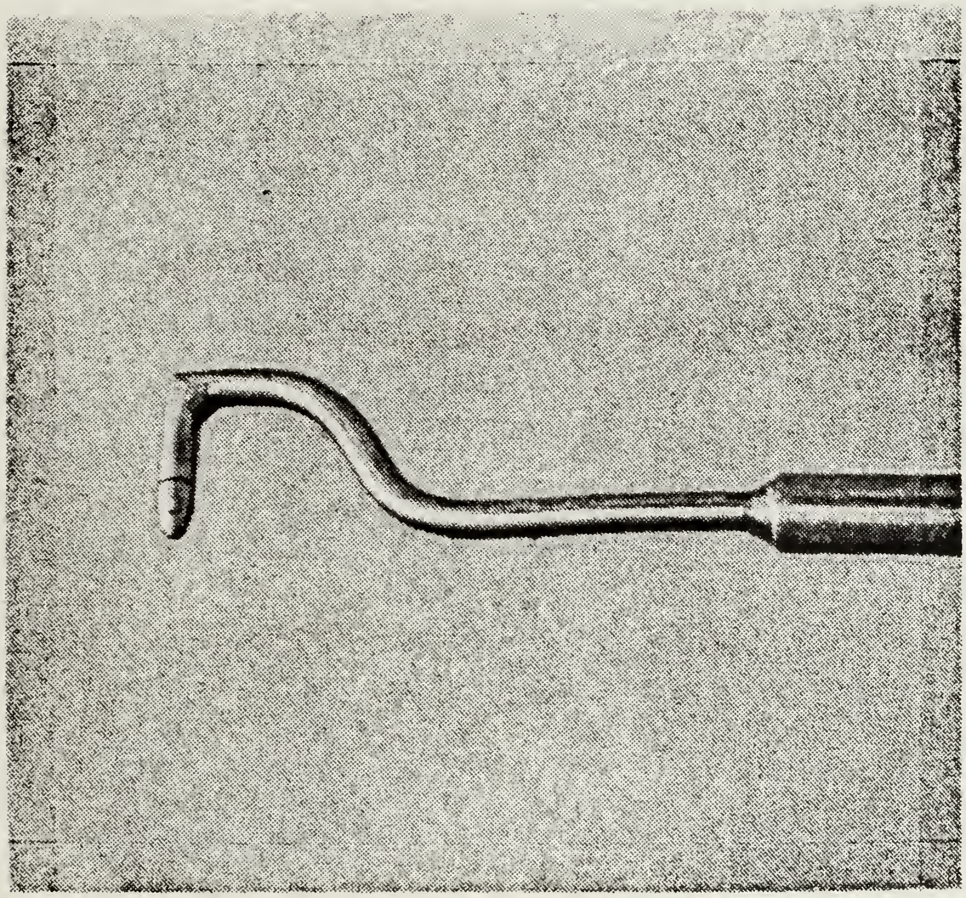
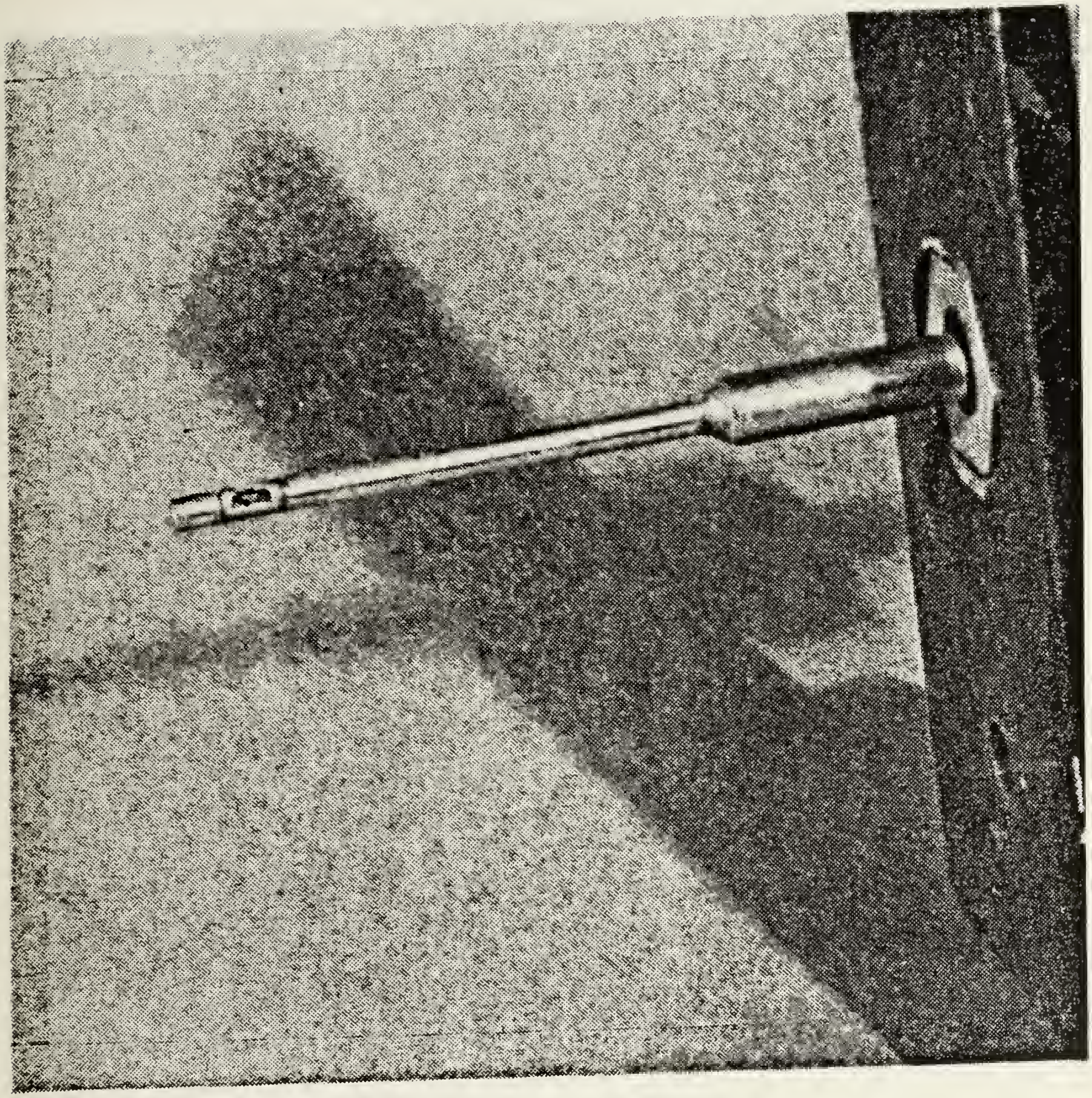


Figure B-2

Upstream Survey Probe

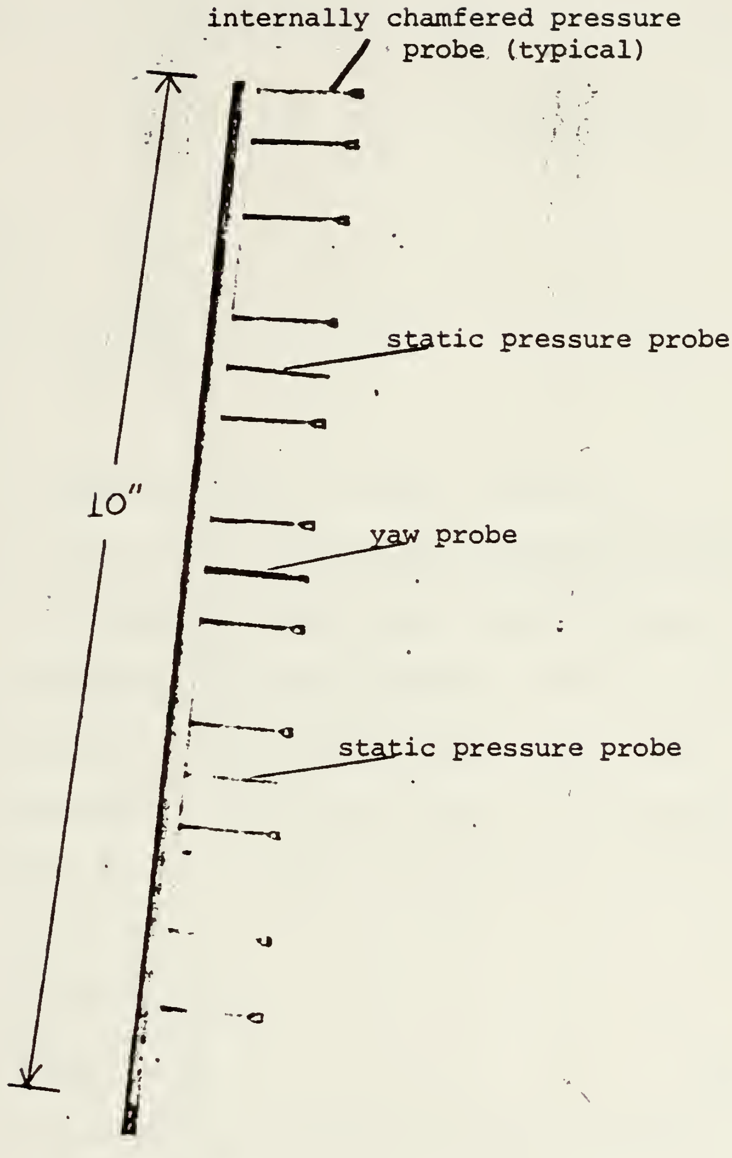


APPENDIX C: RAKE PROBE DESIGN

The rake probe, used for the first surveys of the C-series blade cascade, was designed and manufactured in house (Figure C-1). It consisted of twelve internally chamfered total pressure probes, two static pressure probes, and a centerline yaw angle probe, supported from a $\frac{1}{4}$" diameter metal tube. The rake was installed across the airstream through a slot in the side wall. It was rotated about its axis to align the centerline yaw probe with the airstream. Each probe was connected to one port of the Scanivalve so the sensed pressures could be recorded by the data system. This rake probe could be traversed in the blade-to-blade direction, to enable surveys to be made of total pressure over a large area in a short period of time.

Figure C-1

Rake Probe



APPENDIX D: CALCULATION OF THE AXIAL VELOCITY-DENSITY RATIO (AVDR)

Continuity requires that:

$$\int_0^s \bar{h}_1 \rho_1 V_1 \cos\beta_1 \, d\eta = \int_0^s \bar{h}_2 \rho_2 V_2 \cos\beta_2 \, d\eta \qquad \text{(D-1)}$$

where ρ_i density

V_i velocity

β_1 air inlet angle

β_2 air outlet angle

$\bar{h}_i$ spanwise streamtube depth

s blade spacing

η blade-to-blade dimension, normal to axial direction,

and subscripts 1 and 2 refer to the test cascade inlet and outlet respectively.

As air passes through the cascade, boundary layers build up along the side walls, contracting the streamtube in the spanwise direction. As a measure of the two-dimensionality of the flow, the AVDR is the ratio of the equivalent depths of the streamtube at inlet and outlet. The equivalent streamtube depth, h_i, replaces $\bar{h}_i$ and is taken to be constant over the η dimension:

$$AVDR = \frac{h_1}{h_2} = \frac{\int_0^s \rho_2 V_2 \cos\beta_2 \, d\eta}{\int_0^s \rho_1 V_1 \cos\beta_1 \, d\eta} \qquad \text{(D-2)}$$

In practice, uncommanded variations in blower speed may be experienced during the time required to survey the flow. As a result, the total mass flow rate in the wind tunnel is not exactly constant. Measurements, therefore, actually have a weak (and undesirable) time dependence. Equation (D-2)

assumes all measurements are taken at the same moment in time. More precisely,

$$AVDR = \frac{\int_0^s \rho_2(\eta,t_0)\, V_2(\eta,t_0) \cos\beta_2(\eta,t_0)\, d\eta}{\int_0^s \rho_1(\eta,t_0)\, V_1(\eta,t_0) \cos\beta_1(\eta,t_0)\, d\eta} \tag{D-3}$$

Since no means exists to take all measurements at once, the time dependence of these terms must be removed in some other manner.

In equation (D-3), each integrand has the dimensions (velocity.density). Giving the integrands the symbol m_i, we have:

$$AVDR = \frac{\int_0^s m_2(\eta,t_0)\, d\eta}{\int_0^s m_1(\eta,t_0)\, d\eta} \tag{D-4}$$

Now, assume a function, m_{ref}, can be found, with dimensions (velocity. density), such that:

$$f_i(\eta,t) = \frac{m_i(\eta,t)}{m_{ref}(t)} = k_i(\eta) \tag{D-5}$$

where k_i is not a function of time (that is, it is not dependent on tunnel air supply conditions). Furthermore,

$$AVDR = AVDR\left(\frac{m_{ref}(t_0)}{m_{ref}(t_0)}\right) = \frac{\left[\frac{\int_0^s m_2(\eta,t_0)\, d\eta}{m_{ref}(t_0)}\right]}{\left[\frac{\int_0^s m_1(\eta,t_0)\, d\eta}{m_{ref}(t_0)}\right]} \tag{D-6}$$

Since m_{ref} is not a function of η, it may be taken inside the integral, so that

$$AVDR = \frac{\int_0^s \frac{m_2(\eta,t_0)}{m_{ref}(t_0)}\, d\eta}{\int_0^s \frac{m_1(\eta,t_0)}{m_{ref}(t_0)}\, d\eta} \tag{D-7}$$

Now consider the integrand of the numerator term. By equation (D-5), the integrand is not a function of time as long as m_2 and m_{ref} are measured at the same time, t_0. In practice, where discrete measurements are taken and a numerical integration is performed, it is required only that m_2 and m_{ref} be measured at the same time for the same data point. In this way, m_2 and m_{ref} may vary with time, but their ratio (k_2) remains a function of η only.

Applying the same argument to the integrand in the denominator in equation (D-7), it can be seen that this integrand is $k_1(\eta)$. Furthermore, there is no requirement that both numerator and denominator <u>integrands</u> be measured at the same time, since each is, independently, a function of η only. Therefore:

$$AVDR = \frac{\int_0^S k_2(\eta)\,d\eta}{\int_0^S k_1(\eta)\,d\eta} \tag{D-8}$$

In this manner, the time dependence of the measured "velocity-densities" can be eliminated.

One way to generate such a "reference velocity-density" is to establish a reference density and a reference velocity which, when multiplied together, form a quantity which satisfies equation (D-5). We now also assume β_1 and β_2 are not time dependent. This is justified by the assumption that small changes in inlet dynamic pressure will have little effect on the air angles. Then,

$$AVDR = \frac{\int_0^S \left(\frac{\rho_2(\eta,t_0)}{\rho_{ref}(t_0)}\right)\cdot\left(\frac{V_2(\eta,t_0)}{V_{ref}(t_0)}\right)\cos\beta_2(\eta)\,d\eta}{\int_0^S \left(\frac{\rho_1(\eta,t_1)}{\rho_{ref}(t_1)}\right)\cdot\left(\frac{V_1(\eta,t_1)}{V_{ref}(t_1)}\right)\cos\beta_1(\eta)\,d\eta} \tag{D-9}$$

where subscripts on t indicate which measurements must be taken simultaneously.

Subject to the assumptions that

1. The air acts as a perfect gas,
2. The specific heats are constant, and
3. The total temperature is a function of time only (not of position in the wind tunnel),

the following gas dynamic relationships can be used to express the integrands:

$$\rho = \rho_t\left[1 - X^2\right]^{\frac{1}{\gamma-1}} \tag{D-10}$$

$$\rho_t = \frac{p_t}{RT_t} \tag{D-11}$$

$$V = X V_t = X\sqrt{2c_p T_t} \tag{D-12}$$

where subscript t refers to "total" quantities, and $V_t = \sqrt{2c_p T_t}$ is the "limiting" velocity. Then,

$$\rho V = \left(\frac{p_t}{RT_t}\right)\left[1 - X^2\right]^{\frac{1}{\gamma-1}}\left(X\sqrt{2c_p T_t}\right) \tag{D-13}$$

$$= \frac{p_t X}{\sqrt{T_t}}\left[1 - X^2\right]^{\frac{1}{\gamma-1}}\frac{\sqrt{2c_p}}{R} \tag{D-14}$$

so that, at each data point, the integrand can be written as

$$\frac{m_i(\eta,t)}{m_{ref}(t)} = \frac{\frac{p_{t_i}(\eta,t)}{\sqrt{T_t(t)}} X_i(\eta,t)\left[1 - X_i^2(\eta,t)\right]^{\frac{1}{\gamma-1}}\frac{\sqrt{2c_p}}{R}\cos\beta_i(\eta)}{\frac{p_{t_{ref}}(t)}{\sqrt{T_t(t)}} X_{ref}(t)\left[1 - X_{ref}^2(t)\right]^{\frac{1}{\gamma-1}}\frac{\sqrt{2c_p}}{R}} \tag{D-15}$$

or,

$$\frac{m_i(\eta,t_j)}{m_{ref}(t_j)} = \left(\frac{p_{t_i}(\eta,t_j)}{p_{t_{ref}}(t_j)}\right)\left(\frac{X_i(\eta,t_j)}{X_{ref}(t_j)}\right)\left[\frac{1 - X_i^2(\eta,t_j)}{1 - X_{ref}^2(t_j)}\right]^{\frac{1}{\gamma-1}}\cos\beta_i(\eta) \tag{D-16}$$

so that, finally,

$$AVDR = \frac{\int_0^s \left(\frac{p_{t_2}(\eta,t_0)}{p_{t_{ref}}(t_0)}\right)\left(\frac{X_2(\eta,t_0)}{X_{ref}(t_0)}\right)\left[\frac{1 - X_2^2(\eta,t_0)}{1 - X_{ref}^2(t_0)}\right]^{\frac{1}{\gamma-1}}\cos\beta_2(\eta)\,d\eta}{\int_0^s \left(\frac{p_{t_1}(\eta,t_1)}{p_{t_{ref}}(t_1)}\right)\left(\frac{X_1(\eta,t_1)}{X_{ref}(t_1)}\right)\left[\frac{1 - X_1^2(\eta,t_1)}{1 - X_{ref}^2(t_1)}\right]^{\frac{1}{\gamma-1}}\cos\beta_1(\eta)\,d\eta} \tag{D-17}$$

The final assumption is that the plenum pressure satisfies the conditions imposed on $p_{t_{ref}}$, and that the conditions imposed on X_{ref} can be satisfied

by the quantity

$$X_{ref} = \sqrt{1 - \left(\frac{p_{ref}}{p_{t_{ref}}}\right)^{\frac{\gamma-1}{\gamma}}} \tag{D-18}$$

where p_{ref} is the lower wall static pressure.

No testing was done to examine these last two assumptions. Consequently, it is possible that, in analyzing the data in this way, the time dependence of the measurements was only approximately, and not entirely, eliminated. Elimination of the time dependence would require the measurement of reference quantities which satisfy equation (D-5) exactly.

The X_i were calculated by application of the survey probe calibration. The p_{t_i} and β_i were measured directly by the probe. The AVDR was calculated by numerical integration of equation (D-17).

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